

**A LABORATORY INVESTIGATION
OF FACTORS AFFECTING
THE SLIPPERINESS OF
BITUMINOUS PAVING MIXTURES**

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by

JOHN W. SHUPE

FINAL REPORT

A LABORATORY INVESTIGATION OF FACTORS AFFECTING THE SLIPPERINESS OF BITUMINOUS PAVING MIXTURES

TO: K. B. Woods, Director
Joint Highway Research Project

May 21, 1958

FROM: H. L. Michael, Assistant Director

File: 9-6-4
Project: C-36-53D

Attached is a copy of a report entitled, "A Laboratory Investigation of Factors Affecting the Slipperiness of Bituminous Paving Mixtures," by Mr. John W. Shupe, Research Fellow. The project was under the supervision of W. H. Goetz and was used by Mr. Shupe in partial fulfillment of the requirements for the Ph. D. degree.

Although Mr. Shupe was a Research Fellow with his salary not paid by the Project, he was given assistance in the form of equipment, material, and extra labor in the conduct of this thesis from project funds. A paper has already been prepared from this report, and it is anticipated that the research initiated by Mr. Shupe will be continued. We consider the research reported herein to be both important and timely.

Respectfully submitted,

H. L. Michael

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by

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Joint Highway Research Project

Project No: C-36-53D

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Purdue University
Lafayette, Indiana

May 21, 1958

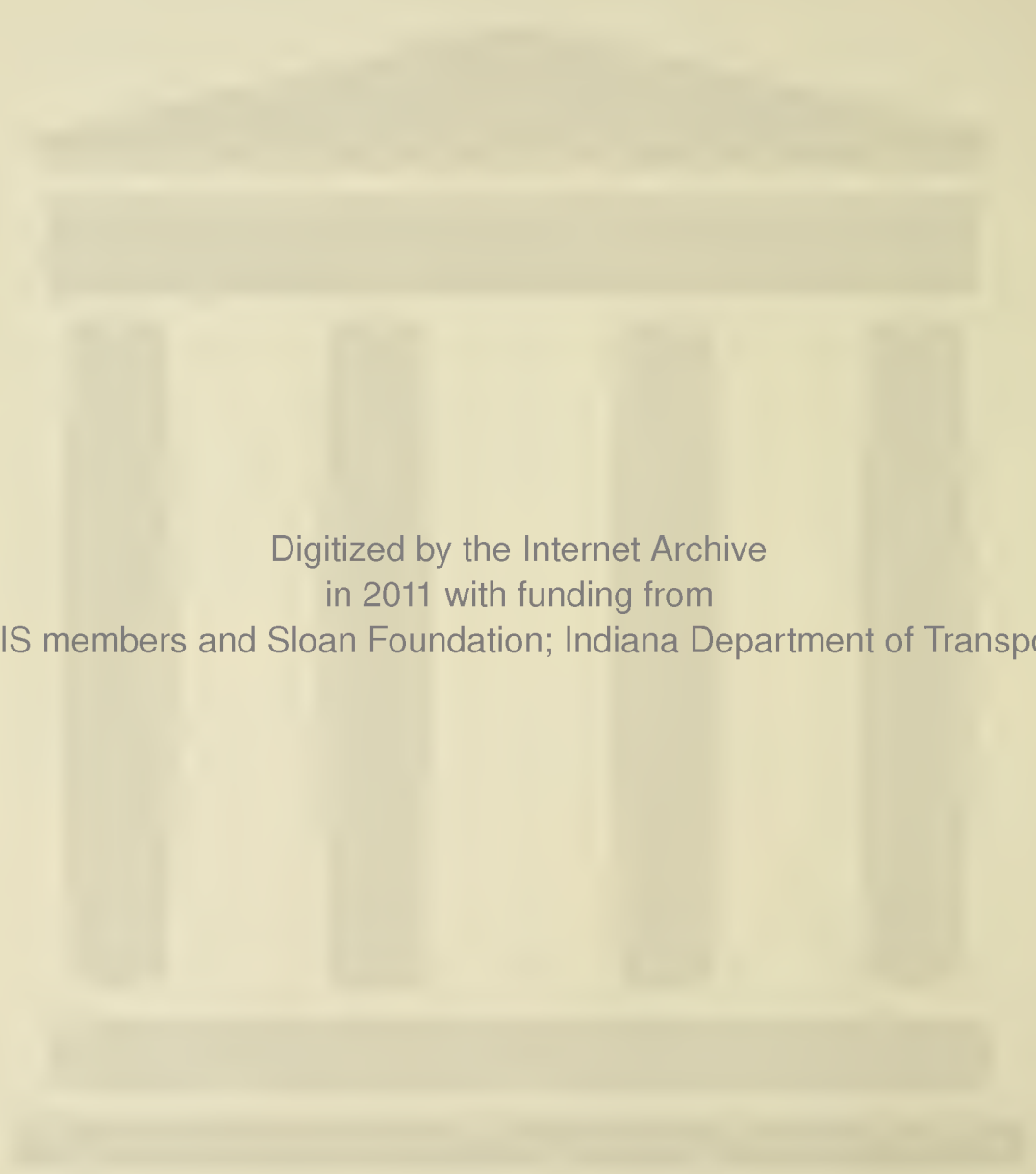
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TABLE OF CONTENTS

	Page
LIST OF FIGURES	v
LIST OF TABLES	vii
ABSTRACT.	viii
INTRODUCTION.	1
General Considerations on Pavement Slipperiness. .	3
Objectives of Study in Relation to Previous Research	6
REVIEW OF LITERATURE.	11
Field Investigations	12
Research in the United States	12
Research in Europe.	19
Laboratory Investigations.	23
Non-Skid Pavement Surfaces	26
DEVELOPMENT OF LABORATORY TESTING PROCEDURE	35
The Laboratory Skid Test Apparatus	37
Equipment and Procedure for Simulating Traffic Wear	49
FIELD CORRELATION STUDY	60
Field Test Equipment and Procedure	60
Preparation of Test Specimens from Pavement Cores. .	63
Description of Highway Test Sections	66
Discussion of Field Correlation Results.	69
PREPARATION OF THE STANDARD LABORATORY SPECIMEN	79
Materials.	80
Batching, Mixing, and Molding Procedure.	84
THE EFFECT OF THE TYPE OF AGGREGATE ON THE SKIDDING RESISTANCE OF BITUMINOUS MIXTURES	88
Description of the Aggregates	90
Discussion of Testing Procedure.	95
Results of the Laboratory Skid Tests	98
Discussion of the Skid Test Results.	105

	Page
THE EFFECT OF SURFACE TEXTURE AND AGGREGATE SHAPE ON PAVEMENT SLIPPERINESS.	113
Surface Texture Investigation.	114
Particle Shape Investigation	124
THE SKIDDING RESISTANCE OF SELECTED DENSE-TEXTURED MIXTURES	128
Description of Materials and Tests	129
Discussion of Results.	133
BLENDING OF SKID-RESISTANT MATERIALS WITH A POLISH-SUSCEPTIBLE AGGREGATE.	138
Coarse Aggregate Substitution.	139
Fine Aggregate Substitution.	142
Fine Aggregate Combination	146
SUMMARY OF RESULTS.	154
CONCLUSIONS	158
SUGGESTIONS FOR FUTURE RESEARCH	162
BIBLIOGRAPHY.	164
APPENDIX A.	169
APPENDIX B.	170
VITA.	178

LIST OF FIGURES

Table	Page
1. Schematic Diagram of Laboratory Skid-Test Apparatus	38
2. Laboratory Skid-Test Apparatus.	39
3. Testing Shoe for Skid-Test Apparatus.	41
4. Rubber Testing Shoe	42
5. Oscillograms from the Laboratory Skid-Test Apparatus	45
6. Conical Rollers for Obtaining Particle Orientation at the Surface of the Test Specimen .	52
7. Rolling Test Specimen in the Minitrack Apparatus.	53
8. Surface Texture at the Completion of the Wearing Procedure	59
9. Field Skid Test Equipment	61
10. Cross Sections of Pavement Cores Mounted in Mortar for Testing	65
11. Representative Surfaces of Highway Test Sections.	68
12. Comparison Between Field and Laboratory Skid-Test Measurements.	72
13. Gradation Curve for Standard Laboratory Mixture .	83
14. Laboratory Vibration Equipment and Test Specimen Mold.	87
15. Photomicrographs of Limestone Thin Sections . . .	93
16. Photomicrographs of Thin Sections of "Resistant" Aggregates.	94
17. Skidding Resistance of Bituminous Mixtures at the Completion of the Fine Polish Cycle	103
18. Variation in Skid Resistance of Bituminous Mixtures with Wear.	104

Table	Page
19. Correlation Between CaCO_3 Content and Polishing Susceptibility.	111
20. Surface Texture of Test Specimens	117
21a. Effect of Surface Texture - Limestone	119
21b. Effect of Surface Texture - Rhyolite and Sandstone	120
22. Comparison of Dense and Open Textured Bituminous Mixtures.	122
23. Effect of Aggregate Shape on Skidding Resistance.	125
24. Enlarged Photographs of Six Fine Aggregates	131
25. Skidding Resistance of Selected Dense-Textured Specimens	135
26. Effect of Coarse Aggregate Replacement.	141
27a. Effect of Fine Aggregate Replacement; S-2 and SL-1.	144
27b. Effect of Fine Aggregate Replacement; SL-2 and Lafayette Sand.	145
28. Effect of Combining Non-Skid Material	148
29. Summary of Blending Study	150

LIST OF TABLES

Table	Page
1. Summary of Field and Laboratory Skid-Test Results.	70
2. Results of Standard Tests on Asphalt Cement. . . .	81
3. Indiana Specification Limits for Hot Asphaltic Concrete-Type B and Mixture Composition Used for Standard Laboratory Specimens.	82
4. Results of Physical Tests on the Mineral Aggregates	91
5. A Partial Chemical Analysis of the Twelve Limestones Included in the Program of Research . .	96
6. Summary of Results on the Polishing of Bituminous Mixtures Containing Different Types of Aggregate .	99
7. Gradation of the Surface Texture Specimens	115
8. Relative Resistance Values for Surface Texture Specimens.	118
9. Mixture Composition of Dense-Textured Specimens. .	130
10. Summary of Results on the Skidding Resistance of Selected Dense-Textured Specimens.	134

ABSTRACT

Shupe, John Wallace. Ph.D., Purdue University, June, 1958. A Laboratory Investigation of Factors Affecting the Slipperiness of Bituminous Paving Mixtures. Major Professor: W. H. Goetz.

This report lists the desirable features that should be included in a laboratory method for evaluating the skidding resistance of different types of pavement surfaces, and discusses them in light of previous research. The laboratory skid-test apparatus, resulting from an endeavor to incorporate these desirable features into the design, is described. This equipment measures and records the frictional force developed between a 6-inch diameter test specimen and a rubber testing shoe for a relative speed between the two sliding surfaces, at the mean radius of the area of contact, of approximately 30 mph.

In order to use this skid-test apparatus with some degree of confidence, a field correlation study was performed on 18 different bituminous pavement surfaces. The skidding resistance in the wet condition was first determined for each of the surface types with the passenger car stopping-distance equipment of the Indiana Department of Highways. Three specimens were then cored from each of the road-test locations and tested in the laboratory skid-test

apparatus. The results of these two methods are compared and, in general, show good agreement.

A procedure, with associated instrumentation, was also developed for simulating the wear and polishing effect that a pavement surface receives under the action of traffic. This rather involved procedure includes kneading the test specimen with conical rollers to obtain proper particle orientation, and "polishing" it in both the modified Mini-track and in the skid-test apparatus itself.

The skidding resistance after various degrees of wear was determined for bituminous mixtures made with 22 different aggregates. Results of these tests indicated the following relationships:

1. Mixtures made with sandstone possessed the best anti-skid resistance of all of the aggregate types tested.
2. Bituminous mixtures containing limestone exhibited poorer anti-skid characteristics, as a group, than mixtures made with other aggregate types.
3. There was an appreciable difference in the skidding resistance of bituminous mixtures containing different types of limestones, with the dolomitic limestones exhibiting better characteristics than limestones high in calcium carbonate.

A petrographic analysis was performed on each of the 22 aggregates, as well as a partial chemical analysis on each of the 12 limestones. The skidding characteristics

are discussed with respect to the basic properties of the aggregates.

The effect of surface texture, primarily as determined by gradation, on the skidding resistance of bituminous mixtures was evaluated for four different aggregate types. It was found that for a given aggregate, if the surface did not become flushed with asphalt, the dense-textured specimens developed higher anti-skid resistance than open-textured surfaces.

The effect of initial aggregate shape was also evaluated by comparing the skidding characteristics of mixtures containing freshly-crushed aggregate with those made with the same type of aggregate after it had been rounded in a Los Angeles abrasion machine. Mixtures containing the freshly-crushed aggregate exhibited better skidding resistance than those made with the rounded aggregate in the initial phase of the wear and polish procedure, but after an appreciable amount of wear in the laboratory equipment the rounded-aggregate specimens possessed anti-skid resistances equal to those of specimens containing freshly-crushed aggregate.

A series of skid-resistance tests was also performed on selected dense-graded mixtures. One purpose of this phase of the study was to evaluate the skidding resistances of the type of mixtures that have shown up so well in field tests, i.e., the dense silica sand and related Kentucky rock asphalt

surfaces. Another objective was to investigate different types of material as potential blending ingredients for improving the anti-skid characteristics of mixtures made with a polish-susceptible limestone. In general, the results of this study substantiated the prevailing opinion as to the high skidding resistance of dense surfaces containing hard, angular quartz particles.

The final phase of this study investigated the effectiveness of different blending procedures on improving the skidding resistance of specimens containing a polish-susceptible limestone. Six different blending materials were used, both as combination and as replacement material. Of the six blending ingredients investigated, silica sand was the most effective in improving the anti-skid characteristics of a bituminous mixture made with a polish-susceptible aggregate.

TERMINOLOGY

In a study of pavement slipperiness it is important that the terms used in describing the pavement surface are well defined. The word, "texture", has many different meanings to different people. However, for the purposes of this thesis the terms, "dense-textured" and "open-textured", pertain to the degree of openness of the surface as affected both by the gradation and the size of the aggregate.

A dense-textured surface may consist entirely of fine aggregate, or may contain appreciable amounts of coarse aggregate. An open-graded silica sand or Kentucky rock asphalt surface, composed of small quartz particles, is considered to be dense-textured in this discussion of pavement slipperiness since the area of each individual surface void is small. Similarly, a dense-graded bituminous concrete containing coarse aggregate would possess a dense-textured surface, if no sizable voids were present at the surface.

An open-textured surface, as considered in this thesis, can be achieved only with bituminous mixtures in which coarse aggregate is present. An open-graded bituminous concrete or a variety of different types of surface treatments can result in an open-textured surface, in which the voids are appreciable in size and the individual coarse aggregate particles are prominent. The total contact area

between the tire and surface may be as great for an open-textured as for a dense-textured surface, but there is greater uniformity of contact over the entire tread pattern with the dense-textured surface.

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INTRODUCTION

The National Safety Council reports in their 1957 edition of "Accident Facts" that during 1956 more than 40,000 persons lost their lives in traffic accidents on the streets and highways of America. In that same period, an additional 1,400,000 motorists and pedestrians received traffic injuries which were disabling beyond the day of the accident.

There are many factors contributing to this appalling number of fatalities and injuries over which the highway engineer has no control. Included in these factors are certain aspects of driver condition or behavior such as excessive speed, reckless driving, drowsiness, and driving while intoxicated. Unfortunately, a large percentage of the serious accidents are attributable, either completely or in part, to these factors which are not greatly influenced by highway design.

However, there are other areas in which the highway engineer can contribute to driving safety, particularly from the standpoint of geometric design. Improved horizontal and vertical alignment to increase sight distances, grade separations at railroad crossings, elimination of potential "death traps" in the form of narrow bridges and

underpasses, limited access, and the construction of multi-lane highways, in which the opposing traffic is separated, are steps in this direction. Although vehicle speed and the incidence of accidents in which drowsiness is a contributing factor are somewhat greater on highways designed to freeway standards, in general both the accident and the fatality rate for these well-designed highways are appreciably below the national average.

Another important matter of consideration to the highway engineer, from the standpoint of driving safety, is the pavement surface itself. This is one of the variables figuring in traffic accidents over which he has a great deal of control, and any accident resulting from a slippery pavement surface is, in part, his responsibility.

Although the proportion of accidents in which a slippery surface is considered to be a contributing factor is relatively small, in terms of human life it is appreciable. The National Safety Council states that 19.4 percent of the fatal accidents in 1956 occurred when the road was wet or icy, but does not indicate the percentage attributable to skidding. The 1956 Summary of Motor Vehicle Traffic Accidents for Indiana reports that in 4,931 of the 57,987 total accidents (slightly over 8-1/2 percent) skidding of the vehicle was apparent. Extending this percentage to the National Safety Council's figures in order to obtain a rough estimate of the national totals, during 1956 approximately 3,400 people were killed and 120,000 injured in

accidents in which the vehicle skidded during some phase of the accident.

These figures present a challenge to the highway engineer. By designing, constructing, and maintaining highways which have high anti-skid characteristics, he can help to minimize the occurrence of accidents involving skidding. It is the purpose of this dissertation to increase the understanding of some of the variables which contribute to slippery pavements, particularly for bituminous surfaces, with the hope that this knowledge may ultimately lead to safer driving conditions on our highways.

General Considerations on Pavement Slipperiness

All pavement surfaces exhibit satisfactory skidding characteristics when dry, unless some foreign matter such as rounded pebbles, oil, or mud is present to lubricate the surface. In fact, some of the surfaces which are dangerously slippery when wet give the highest skidding resistance values when dry. Therefore, the problem is to design pavements which have high anti-skid resistance in the wet condition. Icing and packed snow are special conditions which may contribute to slipperiness of any surface type, so will not be considered.

In the early days of highway design and use, when traffic volume, weight, and speed were all low, the problem of pavement slipperiness was somewhat less complex than

it is today. In the majority of cases the amount of wear was such that portland cement concrete pavements retained their anti-skid characteristics during their entire useful life. The only skidding hazards presented by the so-called high-type pavements, therefore, were with the bituminous surfaces.

There were two reasons that some of the early bituminous surfaces were slick. The most common cause, and one which is still with us today on some of our lower-type surfaces, was the problem of too much asphalt in the pavement surface. This may have been due to poor design or to inadequate control in any of several phases of construction; but whatever the cause, a "bleeding" asphalt surface was extremely slippery when wet. The other factor contributing to slipperiness of bituminous pavements was the use of uncrushed, highly polished sands and gravels. Surface types of this nature exhibit very little resistance to skidding, since a film of water can exist between the tire and the polished aggregate.

Recognizing the above situation, the highway engineer improved his design and control so that today a surface containing an excess of asphalt is the exception rather than the rule. For the most part aggregate specifications have been tightened so that a certain percentage of the gravel must be crushed. As a result, the majority of the highways which have been constructed recently, whether of

portland cement or of bituminous concrete, have had satisfactory skidding characteristics when new. Unfortunately, and this is one of the important problems currently confronting the highway engineer, on many of these surfaces, this initial anti-skid resistance has been short lived.

There are many circumstances which combine to cause these surfaces, which 30 years ago would have been entirely satisfactory, to become slippery under the action of today's traffic. The number of vehicles and travel per vehicle have both increased tremendously; the high speed and flexing of low pressure tires exert a "squee-gee" action on the surface, in addition to the relative sliding between tire and pavement due to braking and acceleration; high-pressure truck tires place an increasingly severe unit load on the pavement surface; and the sand and calcium or sodium chloride, frequently used in many localities for deicing, tends to multiply the abrasive effects of the factors previously enumerated.

As a result, it is now necessary not only to build surfaces with good initial skid resistance, but also to give some consideration to the future change in skidding characteristics due to the polishing effects of traffic. This problem is primarily related to the susceptibility of the aggregate particles to polishing, which in turn is affected by surface texture and particle shape. There is little current knowledge, other than experience on specific

surfaces, with which to predict the long term behavior of the many different surface types. This thesis endeavors to increase this knowledge by investigating the polishing characteristics of different aggregates under variable surface texture conditions and discussing the results in terms of the basic geologic properties of the aggregate.

Although all of the experimental data are based upon bituminous mixtures, the relative polishing susceptibility of the various aggregates would probably be similar for portland cement concrete pavements. Subsequent study will investigate this more fully.

Objectives of Study in Relation to Previous Research

As the incidence of slippery pavements due to aggregate polishing has become increasingly apparent during the past decade, interest and research directed toward meeting the problem have also increased. Outstanding work has been done both in Europe and in this country. An indication of the current interest in this subject was the "Symposium on Vehicle Characteristics and Road Surface Properties", a portion of the program of the 37th Annual Meeting of the Highway Research Board in January of 1958, at which time seven excellent papers on various phases of skidding were presented. A more recent development is the International Conference on Skid Prevention, tentatively scheduled to

conduct its first meeting in September of 1958 at the University of Virginia.

In the later part of 1956 when the plan of study for the experimental work resulting in this thesis was formulated, the situation with regard to research in the skidding area was, briefly, as follows. There was a variety of methods for adequately evaluating the relative skidding resistance of highway surfaces. The resulting value, however, whether in the form of a stopping distance, a rate of deceleration, or a coefficient of friction, was a composite value including the influence of a seemingly endless list of variables. For a bituminous surface this list might include the following:

1. The type of bituminous pavement, i.e., whether a bituminous-concrete pavement, seal coat, etc.
2. The source of the asphalt, its classification, and the amount present in the mix.
3. The type of aggregate, its gradation, angularity, and resistance to wear.
4. The physical condition of the highway, which would depend upon such factors as age, amount and nature of traffic, and, for a multilane section, the lane.
5. The surface condition as affected by moisture, oil dripping, worn rubber, and dust.
6. Temperature of both surface and tires.

These different variables, although certainly not a complete list, give an indication of the wide variety of factors involved in skid resistance measurements. By testing a large number of highway surfaces in the field and performing a statistical analysis on the results, it is possible to develop some general relationships for the various surface types, and some noteworthy contributions have been made in this manner (14, 25, 30). It is not possible, however, in a testing program of this nature to accurately determine the separate effect of each of the important variables.

At this time there had also been published results of various laboratory studies (15, 33, 45). For the most part, however, these programs were either somewhat limited in scope, were a rather minor offshoot of a larger study, or appeared to be unrealistic with respect to forming the sample, evaluating skidding resistance, and/or simulating wear. At any rate, there was no indication of an existing laboratory testing program designed to investigate the relationship between the skidding resistance of a pavement surface and the basic properties of its components. The program of research for this thesis was intended to fill this need.

With this end in mind the following general plan of investigation was formulated:

1. Develop a satisfactory laboratory method for evaluating the skidding resistance of different surface types, adaptable not only to specimens molded in the laboratory but also to those removed from the highway surface.
2. Select a method for determining the skidding resistance of surfaces as they exist in place on the highway, and perform a correlation study between this equipment and the laboratory method. This is necessary in order to ensure that the laboratory values are indicative of actual highway performance.
3. Develop a mixing, molding, and wearing procedure which would result in a specimen with surface characteristics similar to those that an identical mix existing on a heavily traveled highway would exhibit after an appreciable period of wear.
4. Evaluate the skidding resistance of specimens made from 22 different aggregates, representing a cross-section of the common types of aggregate used in highway construction, with particular emphasis on the limestones, which have a reputation for polishing.
5. Perform a petrographic analysis on each of these aggregates and investigate the skidding results in terms of the basic properties of the aggregate.

6. Investigate blending different types of sand or special abrasive material, such as small quantities of carborundum, to improve the resistance to polishing of some of those aggregates which have exhibited the highest tendencies toward becoming slippery.
7. Determine the effect of surface texture for four of the representative aggregates by adjusting the gradation of the mix to give varying degrees of openness to the surface.
8. Investigate the variation in skid resistance due to initial particle shape for four representative aggregates by subjecting the crushed stone to a certain amount of wear in the Los Angeles abrasion machine (omitting the charge of steel balls) before batching and molding the specimen.

The following thesis relates the results of an endeavor to fulfill this program of research.

REVIEW OF LITERATURE

From the very beginning of this modern era of the "high-speed" rubber-tired vehicle, the problem of a slippery riding surface has been a matter of much concern to the driving public and to the highway engineer. Research into the factors contributing to slippery pavements dates back over 30 years, and while the early studies were rather limited in scope, many of the general relationships pertaining to skidding resistance of pavement surfaces were rather well defined in these initial investigations. Most of the early studies were based on field experimentation.

During the last decade research in the area of pavement slipperiness has been intensified, with some of the more recent studies consisting of laboratory investigations. Currently there are at least a dozen agencies in this country engaged in skidding-resistance studies, and probably an equal number abroad. Although this review, with the related bibliography, does not constitute a complete list of all of the research related to pavement slipperiness, it is sufficiently thorough to indicate the major contributions and to illustrate the variety of equipment and diversity of effort that has and is being directed toward this problem.

This review will discuss the literature under three general headings: field investigations, laboratory investigations, and non-skid pavement surfaces.

Field Investigations

Extensive field studies of pavement slipperiness have been performed both in the United States and in Europe. Consideration of the major contributions by continent presents a logical subdivision in reviewing field investigations.

Research in the United States. The first recorded series of skid tests performed in the United States was conducted in 1923 under the direction of T. R. Agg of the Engineering Experiment Station at Iowa State College (2). The skidding resistance of a variety of surface types was determined, both parallel and normal to the direction of travel. The parallel tests were conducted by measuring the force required to pull a Dodge touring car with its rear wheels locked. The normal or sideways coefficient was determined by running the test car and a truck side by side at a slightly diverging angle and measuring the side force generated between the rear wheels of the two vehicles when the lighter car began to skid sideways.

Similar tests were conducted in 1927 with different tire types on both wet and dry surfaces. These tests were

performed at 3 mph. Although there was little consistency of results, the data showed that pavements were more slippery when wet than in the dry condition.

Additional skidding measurements were undertaken at Iowa State College in 1932 and 1933 with R. A. Moyer in charge. The reports of this early research (21, 22, 23) are classics on the subject of determining the skidding resistance of pavement surfaces. Subsequent field investigations have done little to improve the testing procedures and techniques of this early study, other than to take advantage of the developments in measuring and recording equipment which have occurred since that time.

The majority of the testing was accomplished by towing a 2-wheel trailer in such a manner that the towing force was transmitted through an integrating dynamometer. This dynamometer measured the force required to pull the trailer before and after the trailer wheels were locked, and indicated the maximum braking force that each surface was capable of developing. These tests were performed at speeds of from 5 to 40 mph. Lateral skidding resistance was determined by towing the trailer at an angle and measuring the side thrust. Impending skidding resistance was also determined by gradually increasing the braking effort to the point where locking of the wheels was impending. In addition, passenger car stopping-distance tests were performed on a large variety of surface types.



Some of the major findings of Moyer's 1932-33 research were as follows:

1. There is a decrease in the skidding resistance of pavement surfaces with an increase in speed.
2. This decrease is much greater on wet surfaces than on dry.
3. For similar surface types at comparable age, skidding resistance is higher on highways having a low traffic volume than on those with a higher incidence of traffic.
4. All surface types are more slippery when wet than in the dry condition.
5. The best surfaces from the anti-skid standpoint when wet are the sandstone type of rock asphalt surfaces having a "sandpaper" texture.
6. The surfaces which exhibit the poorest wet skid resistance are the glazed or "bleeding" asphalt surfaces.
7. Portland cement concrete pavements do not exhibit the range in values that are noted with bituminous surfaces, and, in general, possess adequate skid resistance.
8. A tire having a good tread pattern will give better skidding protection than a smooth tread tire on a wet surface.
9. A vehicle can develop a much greater braking force in the impending skidding condition, as compared to a wheels-locked skid.

10. A wet pavement surface possesses adequate skidding resistance if it is capable of developing a coefficient of friction of 0.4 in a straight wheels-locked skid.

11. There is a seasonal difference in the skidding resistance of a given pavement surface due to the presence of a traffic film during the summer months.

The Oregon Highway Department made a similar study in the late 1930's using the Iowa State College dynamometer (16). Their findings substantiated the work at Iowa State with regard to the effects of speed, moisture, traffic film, and a glazed surface, but indicated that the best wet anti-skid surfaces were open-textured pavements which provided ready drainage of the water.

Moyer, working with Shupe, continued his work at the University of California and the results of their research are described in numerous publications (25, 26, 27). The truck-trailer equipment was redesigned, with improvements being made in the dynamometer, as well as with the recording and watering equipment, but the basic procedure was essentially unchanged. A new piece of equipment was incorporated into the passenger car stopping-distance method to indicate the coefficient of friction at any given speed during the stop. This was a Statham accelerometer which, in conjunction with a Brush recorder, gave a picture of the deceleration and, therefore, the coefficient of friction



over the entire speed range from the point at which the brakes were applied down to zero speed.

The results of this extensive study in California, covering a period of four years, also agreed very closely with the original Iowa State study on such items as the effects of speed, moisture, traffic film, and impending skid. In general the relative results on the various surface types were also duplicated. However, there were no harsh "sandpaper" rock asphalt surfaces in California, and this study indicated an open-textured angular surface would give the best wet anti-skid resistance for California pavements. It also emphasized the importance of crushed aggregate as compared to rounded aggregate in developing adequate wet skid resistance.

Many other agencies were also making skid-resistance studies in the United States during this period. Stinson and Roberts of Ohio State (43, 44) conducted towed-trailer skidding tests in the early 1930's and developed some of same relationships previously indicated for Moyer's work. They also investigated the effect of tire types and treads, and found that smaller tires with higher unit pressures gave better skidding resistance for a given wheel load than low-pressure tires.

Some excellent work has been done by the Virginia Council of Highway Investigation and Research, initially by Shelburne and Sheppe (38), and more recently by Dillard,



Alwood, and Nichols (6, 30). Testing was done by the passenger car stopping-distance method with speeds varying from 10 to 40 mph. This was primarily an investigation of the effect of different types of pavement surfaces, with variables of testing including different tire compounds and tread types.

The Virginia study obtained results on a wide variety of pavement surfaces with sufficient data on each to indicate fairly definite trends. Again the "sandpaper" texture, as typified by a Kentucky rock asphalt or a silica-sand surface, exhibited the best wet skidding resistance of all surface types investigated. Another important finding was that limestone aggregates will polish in both portland cement and bituminous mixtures, so that the resulting pavement surface is slippery when wet. The more resistant aggregates, such as granite, diabase, and quartz, do not polish as readily.

Whitehurst and Goodwin of Tennessee (48) also noted the tendency of limestone aggregate to polish under the action of traffic, and again established the superiority of a sandpaper finish. Their measurements were made with truck-trailer equipment similar to that used in the California study. They recognized the effect of traffic and age on the skidding characteristics of pavement surfaces and developed an age-traffic index to use in comparing different highway surfaces. This index is equal to the age



of the surface in months, multiplied by the average daily traffic, and divided by one hundred.

Norman of the Bureau of Public Roads (31) conducted a series of passenger car tests which were interesting primarily from the standpoint of the speed at which the brakes were applied. These tests were performed on airport runways at speeds of from 10 to 90 mph. Although this was essentially a brake performance study, it did illustrate the decrease in skidding resistance of wet pavement surfaces at the higher speed ranges.

Indiana is another state for which the skidding resistance of the general surface types has been fairly well established. Grunau and Michael (14) reported on the results obtained on over 250 pavement surfaces with the passenger car stopping-distance method. This study also illustrated the excellent skid resistance of a Kentucky rock asphalt surface and the tendency of limestones to polish. Subsequent research with this equipment, as reported by Shupe (40), indicated the change in skidding resistance with time for two 4-lane test sections, one of portland cement concrete and the other of bituminous concrete. The seasonal effect and the polishing action of traffic, as illustrated by the lower skidding resistance of the outer lane as compared to the passing lane, were both quite apparent in this study.



White and Thompson of Mississippi (46, 47) have reported on the results of passenger car stopping-distance tests on over 200 different pavement surfaces in their state. The results illustrate the marked advantage of crushed gravel, as compared to natural gravel, in developing adequate wet skid resistance.

A recent contribution to the determination of skidding resistance of pavement surfaces has been made by P. C. Skeels of the General Motors Proving Ground (41, 42). He has developed a design for a relatively inexpensive towed-trailer that is similar in many respects to the equipment developed by Moyer in California. This 2-wheel trailer is constructed from the rear end of a post-1950 Buick chassis, with the force required to pull the trailer being measured by strain gages mounted on the torque tube. This equipment has been used extensively in Michigan, as well as in Virginia and the District of Columbia, and appears to be an efficient and economical method of obtaining skid resistance data with a minimum of traffic control and auxiliary apparatus required. Plans of the equipment have been made available by the Proving Ground to any interested agency, and numerous units of this nature will probably be operating on the highways in the near future.

Research in Europe. Interest in pavement slipperiness in Europe, particularly in Great Britain, has matched that of highway engineers in the United States. Skid-test



measurements were made both in Great Britain and France during the 1920's, and it is interesting to note that the first publication of the British Road Research Laboratory (3) was entitled, "Road Surface Resistance to Skidding".

The British have always favored the determination of the sideways coefficient of friction as a measure of skidding resistance of a pavement surface. Early skid measurements (3, 8, 17) were obtained with a motorcycle and side car arrangement, in which the wheel of the side car was mounted at an angle of 18 degrees to the direction of motion of the cycle. The resulting action of the tire was a combination rolling and side skid, and by measuring the lateral thrust, as well as the normal force between the tire and surface, the sideways coefficient of friction could be computed.

The results of these early studies closely paralleled the findings of the American investigators with regard to the effects of speed, moisture, traffic film, excess bitumen at the surface, sandpaper texture, and the polishing action of traffic.

The more recent research of the British has been based partly on the side-car equipment, but also upon three other methods of field determination of skidding resistance (4, 9, 10, 13). The method which has been used most extensively also measures the sideways coefficient of friction. This is accomplished by mounting a conventional wheel



inside a passenger car and, whenever a test measurement is desired, lowering the tire so that it contacts the pavement surface with a given force. This tire is also mounted at an angle to the direction of travel of the vehicle, so the sideways coefficient is obtained.

The British also use the rate of deceleration method of a passenger car with all wheels locked, as described in Moyer's California research, and a single-wheeled trailer. This light-weight trailer is towed by a Jaguar car, and some very interesting results have been obtained with this equipment on airport runways at speeds up to 100 mph. These results indicate that the decrease in friction with increasing speed continues for speeds upward to 100 mph rather than leveling off, as appeared to be the case in previous studies. The decrease in wet friction at high speeds was greater for dense surfaces than for the open-textured pavements, which permit better surface drainage.

Other interesting aspects of the recent British research pertain to aggregate polishing and to the extent and effect of water film thickness. These factors are discussed more fully in a subsequent section on the review of non-skid pavement surfaces.

Engineers of other European countries have also engaged in research on pavement slipperiness. Martin (19) discusses some of the early work of the French, while an excellent summary of the current status of the European



research is presented in Bressot's report as chairman of the Committee on Slipperiness to the 10th International Road Congress in Istanbul (4).

French engineers are using three different "rugosimeters" in the determination of skid resistance of pavement surfaces. Two of these units are towed trailers, one which measures the longitudinal sliding resistance and the other which has its two wheels set at opposing 20 degree angles, with the side thrust between the two wheels indicating the sideways coefficient of friction. The third unit is a large lorry (truck) with two wheels suspended beneath it, also at opposing angles, to determine the sideways coefficient of friction.

The measurement of the skidding resistance of pavement surfaces in both Holland and Italy is made with a 2-wheel trailer, similar in many respects to the type of equipment used in the United States. In both countries the surfaces are evaluated with the wheels locked and sliding longitudinally. In Italy the towing vehicle is a Jeep, while in the Netherlands a large lorry is used.

An interesting method of determining pavement slipperiness has been developed in Spain. It consists of a stationary unit in which a single tire is mounted, lifted above the pavement surface, and driven by an auxiliary motor to the testing rotational speed. The wheel is then



lowered to the pavement surface, with the rate of deceleration of the wheel indicating the coefficient of friction.

Skid resistance measurements are also being made in Sweden and Germany, but no results of these studies have been reported. The results and conclusions summarized for the committee by Bressot were in complete agreement with those previously listed for the United States and British studies; so, consequently, are not repeated.

Laboratory Investigations

The laboratory investigations of factors contributing to the slipperiness of pavement surfaces have been much more limited in scope than the field studies. E. H. Hanson (15) performed a rather extensive program of research at the University of Minnesota in the middle 1930's, but the only surface types investigated were different varieties of iron paving blocks, so the results had rather limited application. The paving blocks were bolted to the periphery of two 6-foot diameter flywheels on which the rear wheels of a passenger car ran. The flywheels were brought up to sufficient angular velocity to simulate 60 mph speed of the test vehicle and the brakes were applied. It is interesting to note that the cast iron paving blocks polished under the action of the rubber tires and had to be redressed occasionally.



Other laboratory investigations, however, have had greater significance with regard to our more common types of pavement surfaces. J. M. Rice of the National Crushed Stone Association (33, 34) reported on the use of a 15-foot diameter test track for investigating the properties of paving mixtures, including skidding resistance. The track, on which a standard bus tire was rolled, was 18 inches wide. Due to the small radius of curvature of the track, there was, in addition to rolling, a twisting action on the test surface during the wearing procedure. This combined action achieved the particle orientation and polish which a surface experiences due to the effect of traffic.

In order to evaluate the slipperiness of the test specimens, Rice used a bicycle tire with the tread on half of the circumference removed. The tire was mounted above the specimen in such a manner that the smooth section would not touch the test surface, but so that the tread section would strike the specimen as the tire turned. An eccentric lead weight actuated the wheel and the amount of rotation after the tread came in contact, which varied from 30 to 100 degrees, was related to the skidding resistance. Although specific results were not presented, it was indicated by Rice that certain aggregates do exhibit poor resistance to polishing.

Stutzenberger and Havens of the Kentucky Department of Highways have recently completed an interesting laboratory



investigation on the polishing characteristics of limestones and sandstones (45). The test specimens were solid 4-inch diameter stone cores which were ground down to their most slippery condition. The texture was evaluated by a 60-degree reflectometer, and the slipperiness was also determined by measuring the force required to turn a rubber disc against the wet surface. Results indicate that limestones, which essentially are fine-grained particles bound in a matrix of similar hardness, will polish, while sandstones undergo a type of coarse wear that does not result in as slippery a surface.

A laboratory method which shows excellent promise as a tool for evaluating the resistance to polishing of different types of pavement surfaces has recently been developed by Goodwin and Whitehurst of the Tennessee Highway Research Program (11). This equipment is similar in some respects to the Spanish apparatus, and consists of a single wheel which is caused to rotate at a constant speed while the tire contacts the wet test surface with a given normal force. The power required to drive the wheel is measured and is related to the skidding resistance of the test surface. This unit is used both for testing and for wearing the test specimens. To date it has been used only with portland cement concrete surfaces, with limited published data, but does indicate that limestones have poor resistance to polishing.



There has been some laboratory work performed in Europe, but very little published in the way of results. Both the British and the French have slipperiness evaluation units which are similar in principle to the Charpy pendulum (4). A rubber strip is attached to the base of the pendulum which, on being released, falls through a given arc, wipes across a test specimen, and, depending upon the degree of slipperiness of the surface, rises a measured amount on the other side. The British also have a laboratory device which operates horizontally and is driven by compressed air. The Spanish rotating wheel can be operated equally well in the laboratory as well as on the pavement surface. However, although the Committee on Slipperiness (4) does indicate a wide variety of European methods for evaluating the slipperiness of surfaces in the laboratory, the results of these studies, if significant, are not currently available.

Non-Skid Pavement Surfaces

As the knowledge on pavement slipperiness has accumulated over the past 30 years, an effort has been made to interpret the data in order to understand the properties of a pavement surface that contribute to its non-skid characteristics, and, conversely, to determine what causes some surfaces to be dangerously slippery when wet. An early analysis of this nature was made in the 1930's by



proponents of each of the four current types of primary highway surfaces. Gray of the Asphalt Institute (12), Fleming of the Portland Cement Association (7), Martin of the General Tarvia Corporation (13), and Schlesinger of the National Paving Brick Association (37) discussed the existing knowledge in their respective area of interest. The total knowledge, as summarized by these four articles, was rather limited.

Since that time field and laboratory investigations have extended the knowledge on the skidding resistance of pavement surfaces, so that today there are many general principles of pavement slipperiness that are rather well defined. A brief summary of the points on which the various field and laboratory investigations, as well as analyses of skidding accident records, are in general agreement will serve to emphasize the factors contributing to pavement slipperiness and to illustrate the area of needed research to which this thesis is directed. The following discussion applies to the skidding resistance of pavement surfaces in the wet condition only.

In all investigations the pavement type which has consistently shown the poorest resistance to skidding has been one in which an excess of bitumen is present at the surface (3, 4, 14, 21, 25). For this reason some investigators (8, 16, 25) favor an open-graded bituminous mixture to a dense one, since there is less likelihood of such a mixture



compacting sufficiently under traffic to result in a "fat" slick surface.

On the other hand the surface which is attributed by many studies to exhibit the best skidding characteristics is one possessing an extremely dense "sandpaper" texture, as typified by a Kentucky rock asphalt or a silica-sand surface (6, 14, 22, 30). It has been noted by one investigator, however, that all so-called "sandpaper" textures will not provide excellent skidding resistance, and an example is cited of a rounded desert sand for which the resistance was low, particularly at high speeds and with a smooth tread tire (25). This leads to the matter of particle shape.

It has become recognized, as the result of numerous studies (8, 13, 25, 48), that a surface composed of rounded aggregate particles cannot develop as much skidding resistance as a surface containing harsh angular aggregate. The majority of the states now require that a certain percentage of the aggregate be crushed for use in paving mixtures, so that most of the new construction on the major highways results in pavement surfaces with good initial skidding characteristics.

However, recent highway studies have indicated that many types of pavement surfaces will polish due to the action of traffic (41, 48). This fact has been substantiated by two excellent analyses of skidding accident records,



one from England (36) and the other from Virginia (30). The British study found that 80 percent of the skidding accidents occurred on open-textured "non-skid" roads, which, although exhibiting a general appearance of possessing good skidding resistance, actually consisted of individual aggregate particles with the sharp edges and corners worn off due to the action of traffic. The Virginia study indicated that the incidence of skidding accidents was 2-1/2 times as great in the three districts in which the available highway aggregate consisted almost exclusively of limestone, as compared to the five districts in which the more polish-resistant aggregate types were used. Further substantiation of the tendency of limestone aggregates to polish is furnished by laboratory investigations (11, 33, 45).

The present consensus of opinion is that the occurrence of a polished aggregate in the pavement surface is now replacing an excess of bitumen as the most common and serious factor contributing to pavement slipperiness. This is due in part to the fact that improved design, construction, and maintenance practices have minimized the presence of "bleeding" asphalt surfaces on our major highway systems. In addition the polishing that a surface receives is a function of the amount and speed of the traffic as well as of the tire design, and it has been only within the last decade that polishing of aggregates has become significant. Virginia, which currently is quite concerned with the



polishing of limestones, completed a rather comprehensive field investigation in 1948, without observing a single case of pavement slipperiness due to aggregate polishing (38). The low-pressure tires of modern design flex during rolling (41) so that there is a scrubbing action, in addition to the rolling action, which takes place whenever a tire rolls over a pavement surface, even if no acceleration or deceleration occurs.

In considering the phenomena of a rubber tire sliding on a pavement surface, the total resisting force is composed of the effect of mechanical interlock, due to envelopment of aggregate particles by the sliding tire, as well as to the so-called true frictional force, which is similar to interlock but on a microscopic scale (20). In the dry condition, there is no water film to impede the development of the frictional forces, and the highest skidding resistance values that have been obtained have been on very dense surfaces with a smooth tread tire, since this combination results in the maximum area of contact (25).

In the wet condition, however, this same combination will result in a pavement surface which is dangerously slippery. The minute irregularities are filled with water, permitting an unbroken film to exist between the tire and the surface. This prevents interlock between the tire and the aggregate, and causes the frictional force to decrease to as low as one-tenth of that developed in the dry state



(25). The British have found that for most aggregates a typical water film thickness will vary from 0.01 to 0.02 of an inch thick (8). Most of this film can be removed rather easily, but the last 0.001 of an inch is very tenacious and, under certain circumstances, this minute film can greatly decrease the resisting force otherwise developed by each aggregate particle.

A tire with a good tread exerts a better wiping action than a smooth tread and also provides built in drainage channels, which cut down on the likelihood of water becoming entrapped between the tire and surface (39). Consequently, a tire with a good tread pattern will develop better skidding resistance on slick, wet surfaces than a smooth-tread tire (25). Similarly, a porous aggregate can relieve the excess hydraulic pressures set up (45) and, in so doing, increase the effective skidding resistance of the surface.

The most effective method, however, of removing the water film from the aggregate particles is to provide a very high unit contact pressure between the tire and the aggregate upon which it is sliding (8). There is some difference of opinion, however, as to how this can best be accomplished. The British advocate an open texture in order to permit the aggregate to "always stand proud", but since some aggregates will polish due to traffic, this is certainly not the total answer. Initially the sharp corners



of an angular piece of aggregate provide little area of contact and, therefore, the unit pressure is high and the water film is penetrated, resulting in higher friction values than for rounded particles (25). However, these high unit pressures also exert an appreciable wearing force on the aggregate, so that the harshness and angularity may be short lived.

The harshness and angularity certainly do not need to be supplied by the coarse aggregate only. The relatively dense Kentucky rock asphalt and silica-sand surfaces, which give such excellent skidding characteristics, are composed of small hard quartz particles (39). Although each individual particle can develop only a small fraction of the frictional force developed by an angular piece of 1/2-inch aggregate, the accumulative effect of the large number of contact points is sufficient to result in a skid-resistant surface. In addition, quartz is No. 7 in the hardness scale and the only material present on the roadway capable of polishing it is more quartz (45). Calcite, which is one of the major constituents of limestones, has a hardness of only three. The individual quartz particles do not become rounded and polished, so the unit pressure between tire and aggregate is high, the water film is displaced, and the skidding resistance is excellent.

The nature of wear of these dense, quartz-particle surfaces is also such as to promote good skidding



resistance. It is similar to the wear that takes place in polishing a sandstone (45), in which the individual quartz particles tear away so that the surface is continually being rejuvenated. A Kentucky rock asphalt surface will retain essentially the same skid resistance during its entire useful life (14). However, in so doing, the useful life may be rather limited, since this continuous wearing away ultimately will result in complete removal of the rock asphalt surfacing. This has occurred on some of the pavement surfaces in Indiana.

The present trend toward supplying anti-skid pavement surfaces, however, seems to favor a relatively thin surfacing, composed of harsh angular particles. Recent publications emphasize this type of treatment (5, 6, 28, 29, 30, 32) as the answer to pavement slipperiness. Ruefer of the New York Port Authority (35) presents an excellent comparison, both in cost and in effectiveness, between thin silica-sand resurfacing and some of the commercial treatments currently being advocated, such as epoxy resins, Vultite, and Rockite. His results indicate an expected life of 4 to 5 years for 1/2-inch thick silica-sand surfaces when the traffic counts are in the nature of 50 to 60 thousand vehicles per day. For more normal traffic the life expectancy increases, with excellent skidding resistance anticipated for the entire useful life of the surface.



While these harsh, dense surfaces have been increasing in popularity as the answer to pavement slipperiness, limestone has acquired a poor reputation as a polish-susceptible aggregate (30, 45, 48). Some states have taken steps to limit or completely eliminate the use of all limestones in the wearing surface of primary highways.

In reviewing the literature, it does not appear that sufficient evidence has been presented to condemn all limestones as unsuitable for surface material. One of the objectives of the research leading to this thesis was to investigate if the prevailing poor opinion with regard to the polishing characteristics of limestone, in general, is justified. Related research has included the effect of aggregate shape, surface texture, and blended non-skid material on the skidding characteristics of bituminous paving mixtures made with different varieties of limestone. These results have been compared with the skidding resistance of mixtures containing other common aggregate types.



DEVELOPMENT OF LABORATORY TESTING PROCEDURE

One of the more important and challenging phases of the entire program of research was the development of the equipment and the procedure for adequately evaluating the skidding resistance of a test specimen in the laboratory. Equally exacting was the selection of a laboratory method, with related instrumentation, for simulating the wear and polishing that a bituminous surface receives under the action of traffic.

In considering the objectives of the program of study in light of previous research, the following requirements seemed essential to the satisfactory determination of the skidding characteristics of a test specimen by a laboratory procedure:

1. The equipment should be adaptable both to specimens molded in the laboratory and to samples removed from the highway surface.
2. Since the wet condition is significant with regard to skidding resistance, provision should be made to ensure that the surface of the specimen is well lubricated during testing.
3. In order to obtain a realistic evaluation, the relative speed between the surface and the sliding



rubber should be high. On the basis of previous field studies (25), a speed of 30 mph appeared to be a reasonable value.

4. The type of rubber, the area of contact, and the normal pressure between the testing shoe and the surface of the specimen should be such that the envelopment of the aggregate particles which occurs during braking of a passenger car on a highway surface is duplicated.
5. The results should be easy to obtain and relatively free from individual bias. To this end automatic recording would be preferable to some method of dial or scale reading during testing.
6. In order to accomplish a large-scale program of research, the equipment should be rugged and capable of producing a large amount of reproducible data over a prolonged period of testing with a minimum of servicing, adjustment, and repair.

With regard to developing an accelerated wearing and polishing procedure, the primary criterion for each test specimen was to duplicate, as nearly as possible, the surface characteristics that a similar mix would exhibit after an appreciable amount of highway service under the action of heavy traffic.



The Laboratory Skid-Test Apparatus

With the objectives listed in the previous section to serve as a guide, plans were drawn up, and the laboratory skid-test apparatus, as illustrated in Figures 1 and 2, was constructed. The following discussion of the essential features of the skid-test apparatus, and a brief explanation as to the reasoning behind certain design features, will make reference to Figure 1, the Schematic Diagram of Laboratory Skid-Test Apparatus.

The power required to maintain a constant rotational speed of the test specimen during testing is supplied by a 40 hp electric motor (1)*. Anticipated torque requirements were only about one-half of this value, but since this heavier unit was available it was incorporated into the design. This required a sturdier frame than otherwise would have been necessary, but resulted in an over-all saving when compared to the cost of a smaller motor. It also provided a margin of safety, should subsequent research require a greater torque output.

The power is transmitted to the lower shaft through four V-belts (2). The pulley on the lower shaft (3) is somewhat smaller than that on the motor, so the rotational speed of the lower shaft assembly, including the test specimen, is approximately 2500 rpm as compared to 1760 rpm for

*Circled numbers refer to the corresponding part number in Figure 1.



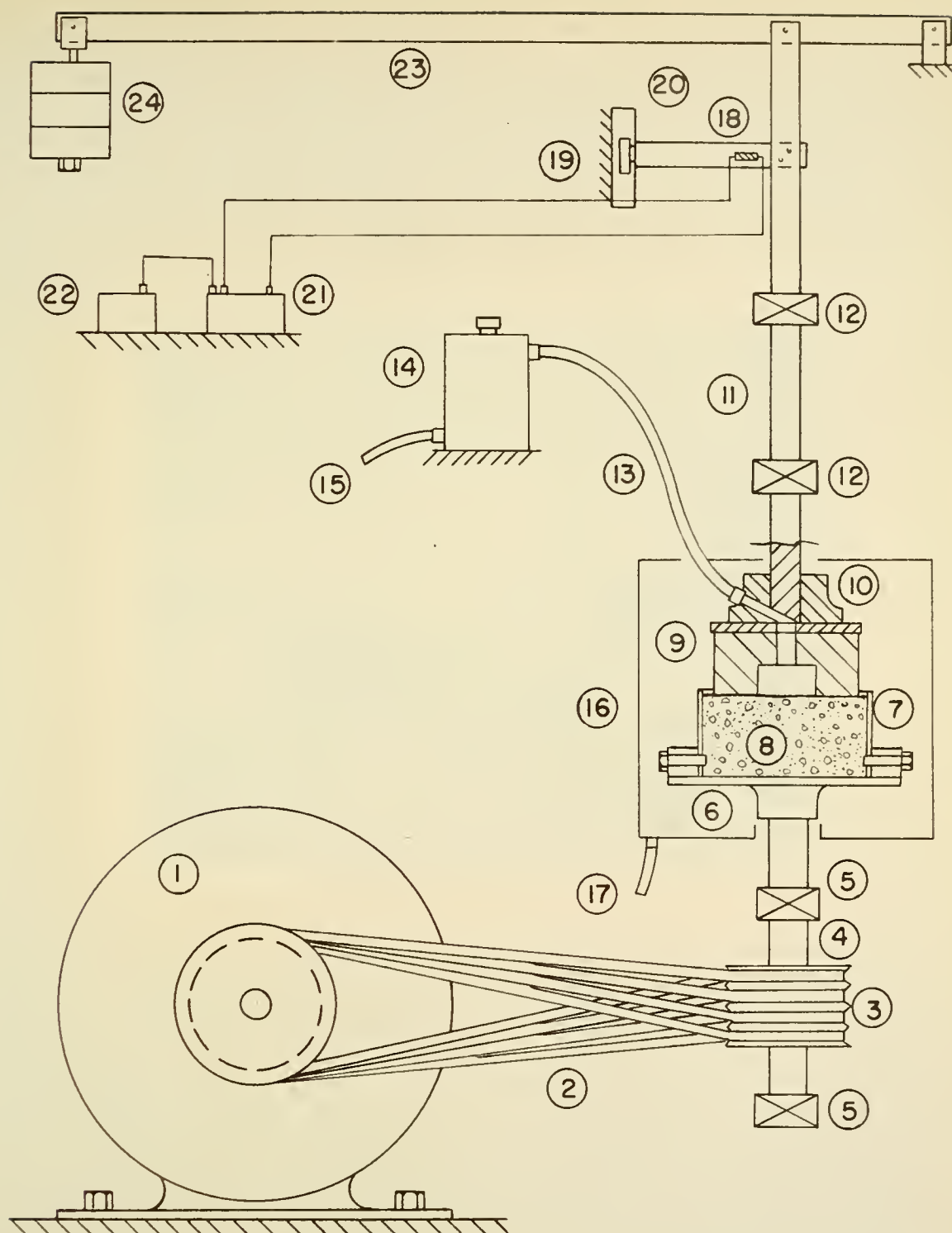


FIG. 1 SCHEMATIC DIAGRAM OF LABORATORY
SKID-TEST APPARATUS



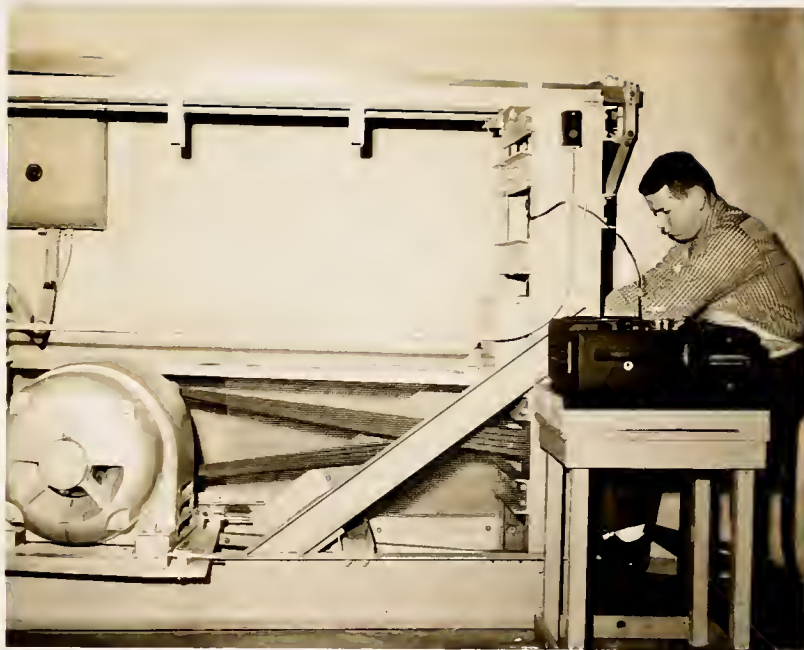


Figure 2. Laboratory Skid-Test Apparatus

the motor. This rotation results in a relative velocity between the test specimen and testing shoe of slightly over 30 mph at the mean radius of the area of contact.

The lower shaft (4) is mounted in two roller thrust-bearings (5), which are rigidly anchored to the frame of the machine. The bracket (6) is fastened to the lower shaft and serves as the base plate for the mold (7) and the test specimen (8).

The testing shoe (9), which is detailed in Figure 3 and illustrated in Figure 4, is made from rubber discs supplied by the Firestone Tire and Rubber Company. The ASTM designation for this rubber is R630B, and it is representative of passenger car tire tread compounds, having a Shore "A" durometer reading of 65. The testing shoe is anchored to the back-up plate by four 1/2-inch diameter pegs and a rubber-to-metal adhesive with the trade name of "Loxite-6000", also furnished by the Firestone Company.

Referring to Figure 3, the area in contact with the test specimen consists of eight segments, each having an area slightly over 1-3/4 square inches, giving a total contact area between testing shoe and test specimen of 14.4 square inches. The total vertical force between the two sliding surfaces during testing is maintained at 400 pounds, resulting in a unit pressure of about 28 psi. The slots were provided in the testing shoe to permit the free passage of water over the test specimen, to prevent overheating



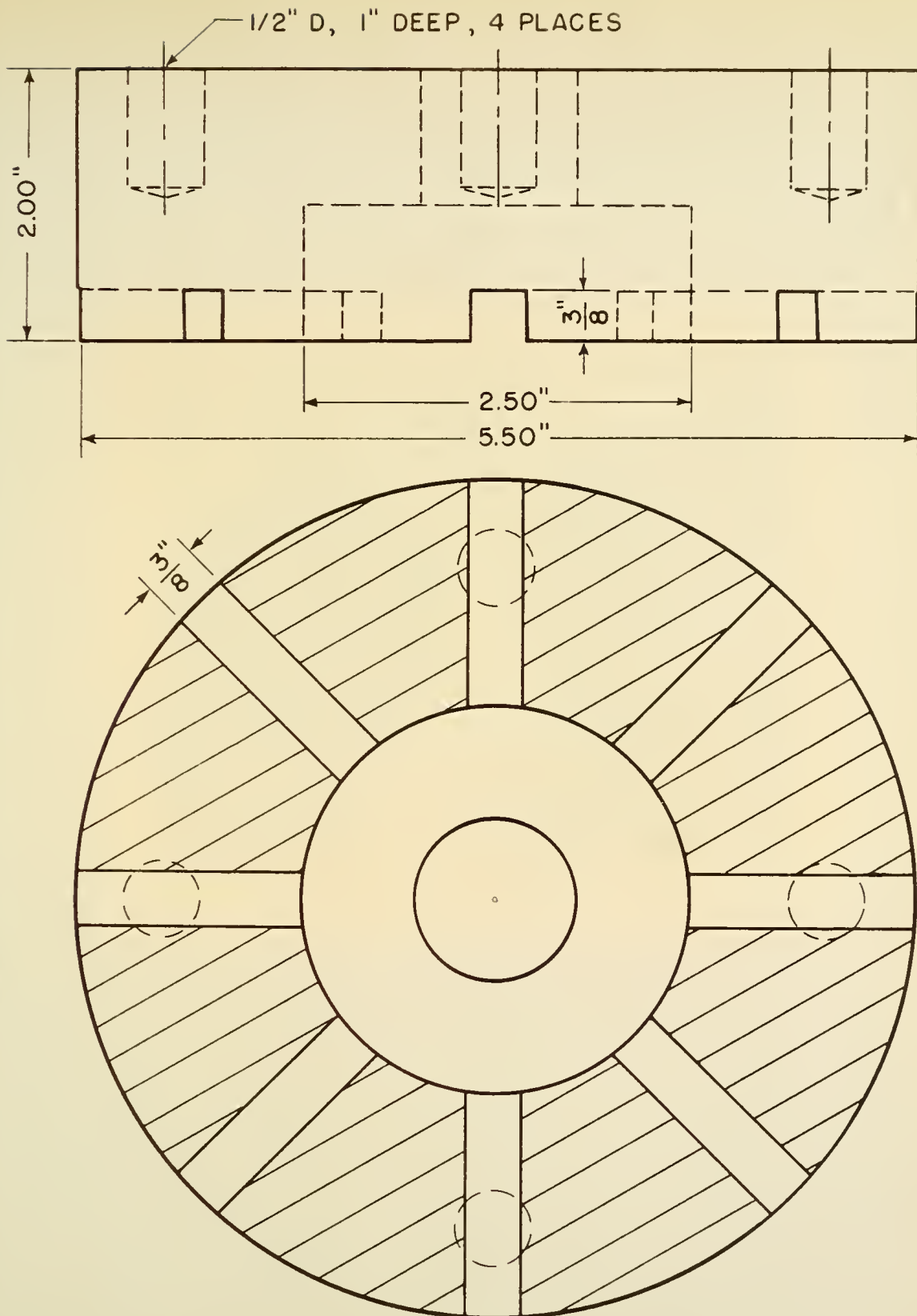


FIG. 3 TESTING SHOE FOR SKID-TEST APPARATUS



Figure 4. Rubber Testing Shoe

of the specimen or testing shoe, and to simulate, to a limited degree, the tread that is present on the majority of vehicular tires.

After prolonged testing the edge of the slot becomes rounded and, occasionally with a particularly abrasive aggregate, the surface of the testing shoe may become scoured. When either of these conditions exists, the testing shoe is removed from the skid-test apparatus and the face redressed. This is done very simply by mounting the shoe and back-up plate in a magnetic chuck and grinding off approximately $1/32$ of an inch of rubber. Before being used again for test measurements the shoe is honed by simulating a test run on a Kentucky rock asphalt specimen.

The testing shoe is attached through a backup plate to the upper bracket (10) which, in turn, is keyed to the top shaft (11). The top shaft is supported in two sleeve bearings (12), which maintain radial alignment of the shoe for all vertical positions. The top shaft assembly does not rotate during testing, and the torque developed in this shaft, due to the sliding friction between the test specimen and testing shoe, is proportional to the skidding resistance of the surface type as represented by the test specimen.

This torque is reacted by a cantilever beam (18), on which are mounted two Baldwin SR-4 strain gages. Original design had these gages located directly on the vertical

shaft, but it was felt that the secondary effects of bending and direct stresses in the shaft would result in inaccuracies in the determination of the torque. The two gages are located at the vertical neutral axis on opposite sides of the beam and are connected into opposing legs of the Wheatstone Bridge circuit, so that any direct force or vertical bending that might be present is not reflected in the torque determination.

In order to ensure that the cantilever torque take-off beam reacts the torque through a fixed lever arm for all vertical positions, a roller-bearing (19) is attached to the end of the beam. This bearing makes essentially point contact with the bearing race (20), which is a one-inch diameter steel rod rigidly attached to the frame and parallel to the top shaft.

The strain gages were attached as close to the top shaft as was practical in order to take advantage of the largest possible bending moment. The torque developed in the shaft results in a bending moment in the beam, causing a change in resistance in the SR-4 strain gages, which is transmitted to the strain analyzer (21) and results in a deflection of the pen in the automatic recorder (22).

Figure 5 illustrates some typical oscillograms for three different surface types. These three test specimens were all cored from highway pavement surfaces, but oscillograms for laboratory specimens are similar in form.

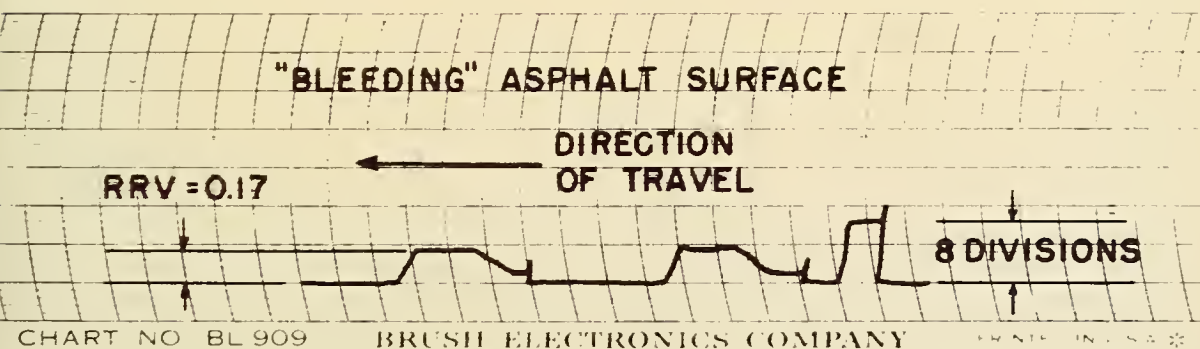
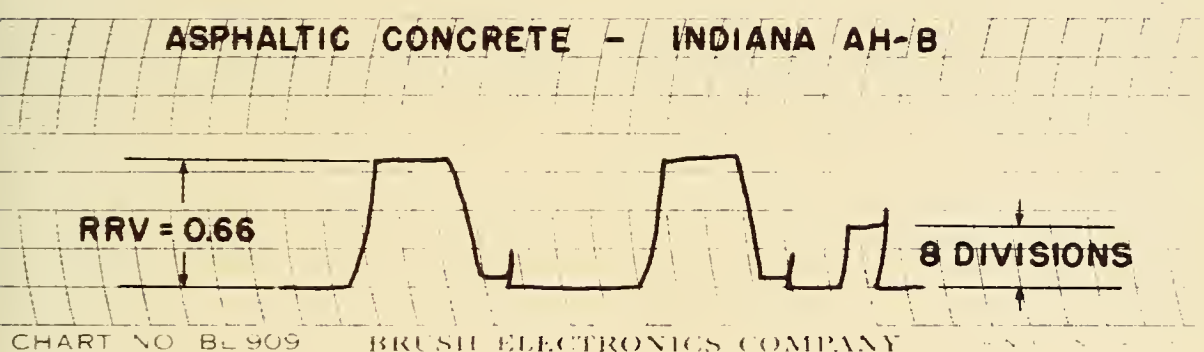
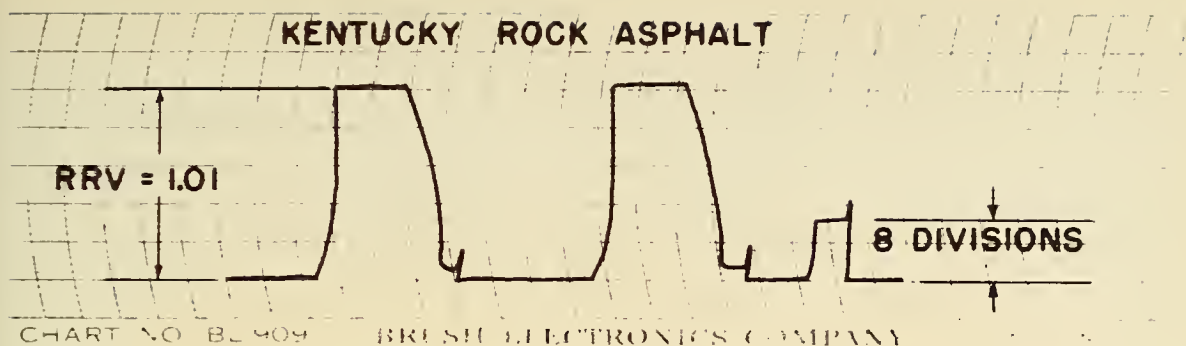


**FIG. 5 OSCILLOGRAMS FROM THE
LABORATORY SKID-TEST APPARATUS**

The skidding resistance of each of the surfaces is represented by a numerical value called the relative resistance value or RRV. This skid-test apparatus, like most of the methods for determining the skidding resistance of test surfaces, evaluates the different surface types on a relative basis. No effort was made to convert this reading to a coefficient of friction. It was decided that since Kentucky rock asphalt surfaces consistently exhibit the best skidding resistance when wet, as has been determined by previous research (14, 22), the attenuation in the analyzer would be adjusted so that the deflection of the pen, due to the torque developed by a Kentucky rock asphalt specimen, would be approximately five major, or 25 of the smaller, divisions. By arbitrarily assigning a value of unity to the resistance developed by the Kentucky rock asphalt, the relative resistance values of the other surface types, with respect to an RRV for Kentucky rock asphalt of approximately 1.00, could be determined to the nearest 0.01.

The three surface types in Figure 5 show relative resistance values of 1.01, 0.66, and 0.17, respectively. This represents the maximum range encountered in the testing program, since Kentucky rock asphalt exhibited the best anti-skid characteristics, and a "bleeding" asphalt surface, the poorest of all the surface types tested.

Before each of the testing records in Figure 5 is noted a blip labeled, "8 divisions". This is the pen deflection caused by the calibration resistance in the analyzer. It was found that by adjusting the a-c gain so that the calibration resistance caused a pen deflection of eight of the small divisions, the deflection resulting from a Kentucky rock asphalt test specimen would be approximately five of the major divisions. Therefore, this 8-division deflection due to the calibration resistance was established as the standard sensitivity, and was adjusted, if necessary, before each test.

Two 3-second skids were made on each test specimen. The relative resistance value was based on the second trace, as illustrated in Figure 5. Frequently the RRV for the first skid fell off rather sharply so that there was as much as 0.06 to 0.08 difference in RRV between the beginning and end of the skid. By the second skid, however, the trace was usually sufficiently stable so that an accurate determination of the RRV was possible. It was felt on the basis of repeated tests that an accuracy of plus or minus 0.01 could be achieved, if care was taken to assure that the 8-division sensitivity was maintained.

A constant load of 400 pounds is applied during testing by attaching a load (24) of 58.7 pounds to the end of the loading bar (23). This bar is pivoted at the far end so that a mechanical advantage of slightly over six is

achieved. This, in addition to the weight of the bar itself and of the upper shaft assembly, gives a constant normal force between the two sliding surfaces during testing of 400 pounds, or an equivalent unit pressure of about 28 psi.

The remaining elements of the skid-test apparatus pertain to the water system, which keeps the test surface in a lubricated condition during testing. The water is admitted to the test specimen through a hole located in the center of the testing shoe (9), after flowing through a passage drilled in the upper-shaft bracket (10) and the upper shaft (11), as illustrated in Figure 1.

A flexible water line (13) is used so that the system can operate for different vertical positions of the upper-shaft assembly. The turbulence chamber (14) has no function in the testing operation, but has an important role in the polishing procedure and is discussed in a later section. Line pressure is maintained at the water inlet (15) and results in a rate of flow of water on the test specimen of 7.5 gallons per minute. All of this water is admitted to the specimen through the center of the testing shoe and flows over the specimen through the slots provided in the shoe.

The water spins from the specimen at 2500 rpm, so a shield (16) is necessary to catch the water and channel it to a drain (17). This shield is intended to be not only

waterproof, but also "bulletproof"; so was constructed from 1/4-inch steel plate. Should a bolt come loose at 2500 rpm or a large piece of aggregate be dislodged from the surface, the shield would be adequate to prevent the flying particle from causing damage to equipment or personnel.

Briefly summarizing the test procedure: first, the motor is turned on, causing the specimen to rotate at 2500 rpm. Next, the water valve is opened and the recording equipment started to establish the zero reading on the oscillogram. Then the weight is lowered manually to allow the full 400-pound force to bear on the test specimen for two 3-second intervals. During this period the frictional torque developed in the top shaft is automatically recorded, indicating the skidding resistance of the test specimen. The weight is then secured and the water, recording equipment, and electric motor turned off. The total time lapse is approximately 15 seconds.

Equipment and Procedure for Simulating Traffic Wear

The procedure and associated instrumentation for simulating the wear and polishing effect that a pavement surface experiences under the action of traffic evolved as a result of investigating different methods of polishing on over a hundred test specimens. Various polishing compounds were used, including carborundum, alundum, emery, quartz, and limestone, varying in particle size from 0.005 to 0.30

millimeter. Contact pressures ranging from 1 to 28 psi were tried at speeds of 33 and 2500 rpm. Polishing was attempted both with a rolling rubber cone and with a sliding rubber disc. The length of time for a given polishing cycle was varied from 30 seconds to 30 minutes, with the number of cycles per given specimen varying from two to twelve.

It was relatively easy to grind the test specimens down, with the skid-test apparatus being used for this purpose. Referring again to Figure 1, a charge of abrasive material was first placed in the turbulence chamber (14). Then as the valve was opened and water rushed into the chamber from the inlet (15), the abrasive was agitated into suspension and flowed down the outlet line (13) to the specimen. The inlet pipe was brazed to the circular brass chamber at an angle of 45 degrees to the tangent to encourage a swirling action, which would permit adequate transport of the abrasive. Calibration tests showed that with full line pressure at the water inlet, less than 5 grams of an initial charge of 500 grams of #40 to #80-mesh sand remained in the turbulence chamber after 60 seconds. For limestone mineral filler, less than a gram was present in the chamber after 60 seconds.

The test specimens were ground with a rubber polishing shoe similar in appearance to the testing shoe of Figures 3 and 4. The outside diameter was 1/4-inch larger and the

inside diameter 1/4-inch smaller than the corresponding dimensions of the testing shoe in order to ensure that an adequate area would be polished for subsequent testing. Also, the rubber compound from which the polishing discs were made was slightly harder than that used in the testing shoes, having an ASTM designation of R730BJ.

By starting with a coarse abrasive and a small contact pressure, to keep from overheating the polishing shoe, the specimen could be ground down to essentially a level datum by decreasing the particle size of the abrasive and increasing the contact pressure as the specimen became progressively smoother. However, a visual comparison of the resulting specimen with a similar mixture cored from the highway showed that there was little similarity between the surface textures of the two. The well-worn highway specimen exhibited a texture which was not a level datum, but one in which the somewhat rounded and highly polished particles of coarse aggregate projected slightly above the surrounding matrix of asphalt and fine aggregate. This condition could not be duplicated merely by grinding down the specimen.

The conical rollers, as illustrated in Figure 6, were intended to supply the rolling action that a surface experiences due to traffic, in order to achieve the particle orientation and arrangement that exists on the highway surface. Figure 7 shows a specimen being rolled at 33 rpm in

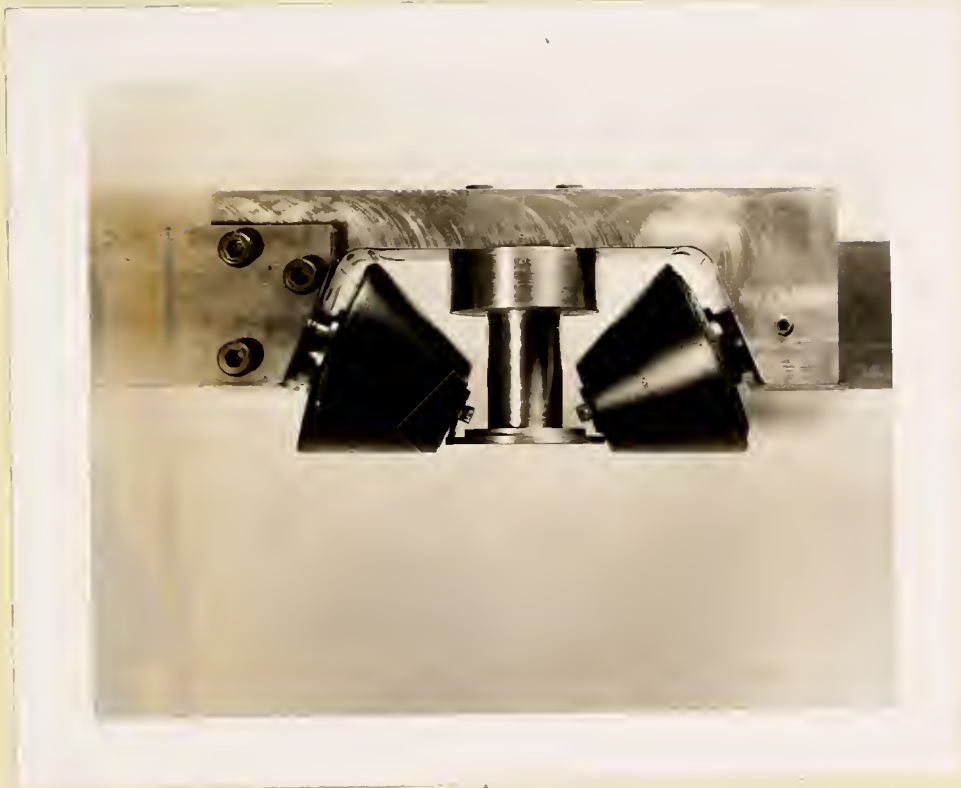


Figure 6. Conical Rubber Rollers for Obtaining Adequate Particle Orientation



Figure 7. Rolling Test Specimen with Conical Rollers in the Minitrack Apparatus

a Minitrack apparatus. This equipment originally was developed some years ago for traffic testing specimens on a circular track with a small rubber tire. Only slight modification was necessary to adapt the existing equipment to accommodate the 6-inch diameter specimen. Rolling in this manner resulted in an over-all densification of the test specimen with the coarse aggregate particles becoming somewhat more prominent at the surface than was noted at the completion of the molding procedure.

Rolling was initially attempted with this equipment without the use of the center post. At 140 F. some of the mixes shoved excessively and bunched up at the center of the specimen. The post was then incorporated into the design, but located flush with the bottom of the rollers. This eliminated the shoving, but since the post took most of the vertical load, only a slight amount of particle reorientation was accomplished. The final position, as shown in Figure 6 with the rollers extended $1/8$ of an inch below the post, represented a compromise in which sufficient confinement was provided without sacrificing an adequate amount of particle orientation.

Another operation which seemed to enhance the effect of the coarse aggregate at the surface was to polish the specimen at 33 rpm in the Minitrack, using the conventional polishing shoe previously described, with limestone mineral filler suspended in water as an abrasive. This operation

polished the coarse aggregate particles slightly, and also appeared to erode away some of the surrounding matrix of fine aggregate and asphalt, so that the resulting surface texture more nearly approximated that of a sample removed from the highway surface. It was necessary to give the specimen a final polish in the skid-test apparatus in order to smooth off the rough edges exposed by this operation.

This left the test surface in a clean, polished condition. By rolling the specimen again at 140 F. for a short time with the conical rollers, a very light asphalt film could be made to coat the aggregate. This coating discolored the aggregate somewhat, but did not result in a solid black asphalt appearance, so seemed more representative of an oily rather than an asphaltic film. It was felt that although this treatment did not exactly duplicate the oil drippings, worn rubber, and debris film that exist on highways during certain seasons of the year (25, 40), the relative resistance values for this final condition would be indicative of the susceptibility of the surface types, as represented by the test specimens, to this seasonal effect.

The rather complicated wear and polishing procedure as finally evolved consists of the following steps:

1. The specimen is rolled for two minutes at 140 F. in the Minitrack at 33 rpm with a total load on the two rollers of 100 pounds.

2. Coarse wear is accomplished in the skid-test apparatus with a contact pressure between the shoe and test specimen of 5 psi. Each specimen is subjected to three wear series as follows:
 - a. 300 grams of #3/0 quartz* for 60 seconds.
 - b. 500 grams of #5/0 quartz* for 60 seconds.
 - c. 400 grams of limestone mineral filler* for 60 seconds.
3. Particle orientation and texture is accomplished in the Minitrack at 33 rpm.
 - a. Two minutes rolling at 140 F. with a total load of 100 pounds on the two rollers.
 - b. Ten minutes of wear, using 10 psi contact pressure with the polishing shoe and 25 grams of limestone mineral filler.
4. Final polish is given the specimen in the skid-test apparatus at 2500 rpm.
 - a. 250 grams limestone mineral filler, 15 psi contact pressure, for 30 seconds.
 - b. 250 grams limestone mineral filler, 28 psi contact pressure, for 30 seconds.
 - c. No abrasive, 28 psi contact pressure, for 30 seconds.
5. The final operation is to coat the aggregate particles in the specimen surface with a light

*Gradation is listed in Appendix A.

asphalt film, simulating seasonal road film, by rolling in the Minitrack at 140 F. for 1 minute with a load of 100 pounds on the conical rollers.

As previously stated, this procedure was intended to result in a specimen which, both in appearance and in skidding resistance, closely duplicated a similar mix after an appreciable amount of traffic wear. It was not the intention to arrive at the ultimate slippery condition for all surface types. However, the above procedure does cause a specimen made with an aggregate having poor polish-resistant characteristics to approach its most slippery condition. It was felt that by holding the polishing effort constant, a relative measure of the resistance to polishing of the different aggregate types could be obtained which would be more realistic than subjecting each of the test specimens to sufficient polishing to cause it to arrive at its most slippery condition.

It was found that extreme polishing could cause test specimens made from the more resistant aggregates, such as high-quartz gravel and rhyolite, to have relative resistance values below 0.4, which is equivalent to a passenger-car stopping distance from 30 mph of approximately 150 feet. Since field tests on surfaces of this nature (30) indicate that these materials are resistant to polishing, these data did not seem realistic.

During a complete polishing cycle each portion of the test area receives over 80,000 individual passes either from the conical rollers or the separate segments of the testing shoe. Figure 8 illustrates the appearance of two typical specimens after being subjected to this polishing series. Figure 8(a) shows a limestone which exhibited poor polishing characteristics, and Figure 8(b) a highly resistant sandstone. These photographs were made following the final polish, but prior to the final rolling which serves only to coat the aggregate slightly.





a. Limestone Test Specimen



b. Sandstone Test Specimen

Figure 8. Surface Texture at the Completion of the Fine Polish Cycle

FIELD CORRELATION STUDY

In order to determine if the laboratory skid-test apparatus would evaluate the various test specimens in a realistic manner, a field correlation study was performed. Passenger car stopping-distance tests were made on selected highway surfaces with the testing equipment of the State Highway Department of Indiana. Cores were obtained from these test sections and the relative resistance values determined in the laboratory. A comparison of the results of these two methods was then made.

Field Test Equipment and Procedure

The passenger car stopping-distance test equipment was developed by the Joint Highway Research Project of Purdue University and is described in detail by Grunau and Michael (14). The equipment was transferred to the State Highway Department of Indiana in 1956, and was made available by this agency for the correlation study.

Briefly, the essential components of this equipment consist of a 1955 Ford 2-door sedan equipped with an electrically-operated, vacuum braking unit for instantly locking all four wheels, and a Wagner Stopmeter, which is a



Figure 9. The Wagner Stopmeter Attached to the Rear of the Test Vehicle

fifth wheel for indicating both the speed at which the brakes are applied and the total distance required to skid to a stop after the brakes are actuated. Figure 9 shows the Wagner Stopmeter attached to the test vehicle, and also the vacuum braking system located in the vehicle luggage compartment.

For this correlation study all skidding tests were performed with the surfaces in a wet condition. A tank truck equipped with spraying apparatus was used for wetting down the surfaces before each test. Traffic control was required both for the watering operation and during the actual testing. A crew of five men were supplied by the State for the wetting and traffic control, while the skidding tests themselves were performed by two members of the Purdue staff.

The following procedure took place at each of the test sections. The surface was first thoroughly drenched with a slow pass of the watering truck. The test vehicle was then brought up to an indicated speed on the Wagner Stopmeter of 30 mph and the brake-actuator button depressed, causing all four wheels to lock. The distance required for the vehicle to skid to a complete stop, as measured by the Wagner Stopmeter, was then recorded. This completed one test. Two more tests of the same section were performed in a like manner with the surface receiving a relatively light water treatment prior to each test.

As previously mentioned, the brakes were applied at an indicated speed on the Wagner Stopmeter of 30 mph. On computing coefficients of friction for some of the test surfaces and comparing these values with results of studies in other states, some doubt arose as to the accuracy of the speedometer. A rough check with a radar speed-determination unit showed that with an indicated speed of 30 mph on the Wagner Stopmeter, the vehicle was actually traveling between 33 and 34 mph. This had no adverse effect on the correlation study, which was merely a comparison of two methods of evaluating the skidding resistance of different test surfaces. However, no comparisons should be made between these results and 30-mph stopping distance measurements of other research studies.

Preparation of Test Specimens from Pavement Cores

Three cores were removed from the pavement at each test section. These cores were taken from the outside wheel track, and were evenly distributed longitudinally along the length of the skidding area of the stopping-distance tests.

The cores were drilled with a Model 12 Abrasive Speed Drill, manufactured by Howe-Simpson, Inc., of Columbus, Ohio. The bit was made from standard steel pipe having a nominal diameter of 6 inches. Silicon carbide abrasive, size #40, was used to aid in cutting. Following the

directions of the manufacturer's manual, it was possible to obtain cores from most of the well-consolidated bituminous mixtures. On two relatively new open-mix type surfaces constructed with gravel it was impossible to obtain cores. The mixture was still too tender, so rather than being ground through, the coarser particles were dislodged from the surrounding matrix and rolled around under the bit, causing the mixture to disintegrate.

It was possible to core at the rate of about 1 inch in 5 minutes for bituminous mixtures made with limestone aggregate. On those pavements containing the harder gravel particles, however, this rate was only about one-third as fast. During the total coring program, which consisted of about 60 percent in limestone and 40 percent in gravel, the rate of wear on the steel bit was about an inch of wear for every 16 inches of core.

The resulting specimen was a core approximately $5\frac{3}{4}$ inches in diameter and, depending upon surface type, anywhere from $\frac{3}{4}$ of an inch to over 3 inches thick. In addition the bottom of some of the specimens were extremely irregular. These specimens were mounted in the molds in a paste consisting of three parts of type I portland cement to one part plaster of Paris, with sufficient water to provide adequate workability. Figure 10 shows sawed-sections of some typical pavement cores. The top specimen is an asphaltic concrete made with limestone; the middle specimen



Figure 10. Cross Sections of Pavement Cores
Mounted in Mortar

is from a new asphaltic concrete pavement containing gravel, in which some difficulty was encountered in obtaining a core; and the bottom specimen shows a 1/2-inch layer of Kentucky rock asphalt on a bituminous-coated gravel base.

After the cementing paste hardened sufficiently, the specimens were tested in the skid-test apparatus in the same manner as for the conventional laboratory test specimens.

Description of Highway Test Sections

Only a brief description of the various test sections is included, since it was not the purpose of this correlation study to evaluate the different surface types, as such, and no systematic sampling was made with regard to selecting sections having comparable traffic and age. As a result, no conclusions should be drawn on the basis of these limited data as to the relative skid resistance of the various surface types.

In planning the correlation study, 32 test sections, representing a wide range of bituminous surface types, were chosen from the west-central area of Indiana. Three stopping-distance skid tests were made at each location. Examination of the test data led to the selection of 20 of these sections as correlation sites from which three test specimens were to be cored. At two of these sites it was

impossible to obtain adequate cores, so the following correlation study was based upon 18 test sections.

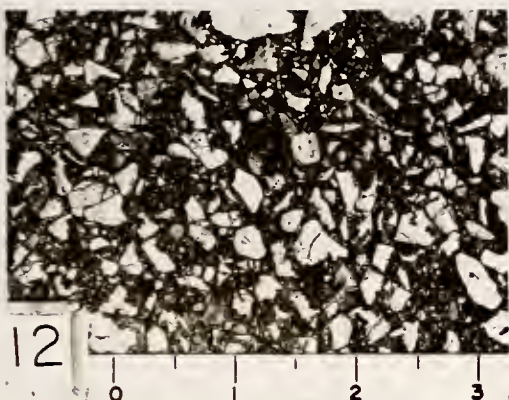
Figure 11 illustrates the general surface types into which these 18 test sections were classified.

Figure 11(a) is representative of those asphaltic concrete surfaces in which the coarse aggregate consisted of limestone. Referring to Table 1, test sections 9, 12, and 13 are included in this classification.

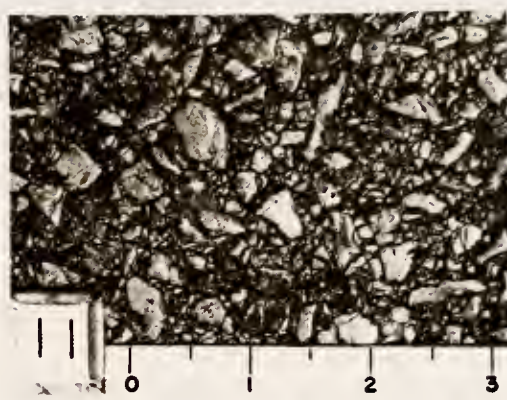
Figure 11(b) is typical of test sections 4, 11, 14, and 26, which are identified rather broadly as limestone surface treatments. All of these surfaces either were given a final surface treatment involving separate applications of asphalt and aggregate, or were of similar texture, so that the resulting area of contact on which the tire skidded consisted almost entirely of coarse aggregate.

Figures 11(c) and 11(d) represent, respectively, the same surface types as Figures 11(a) and 11(b), except that gravel rather than limestone was used in these bituminous mixtures. Test sections 3, 5, and 6 are asphaltic concretes made with gravel, and sections 1, 16, 23, and 27 are gravel surface treatments.

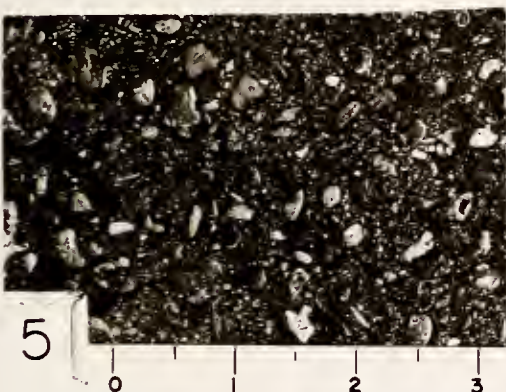
Three Kentucky rock asphalt surfaces were included in this study. This material occurs in Kentucky in a formation in which a Mississippian sandstone is impregnated with asphalt. This type of surface is very uniform and fine-



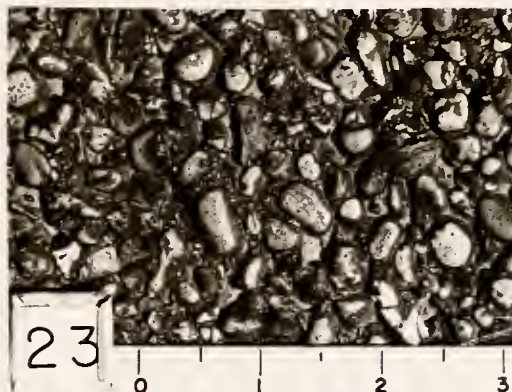
A. ASPHALTIC CONCRETE
LIMESTONE



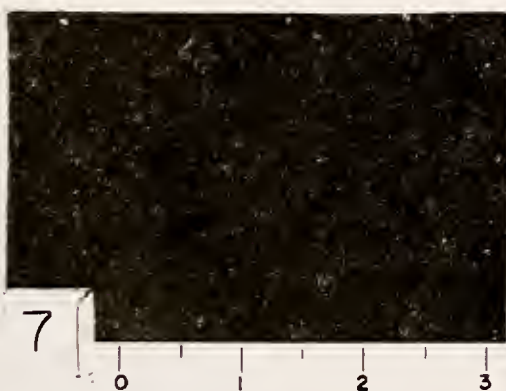
B. SURFACE TREATMENT
LIMESTONE



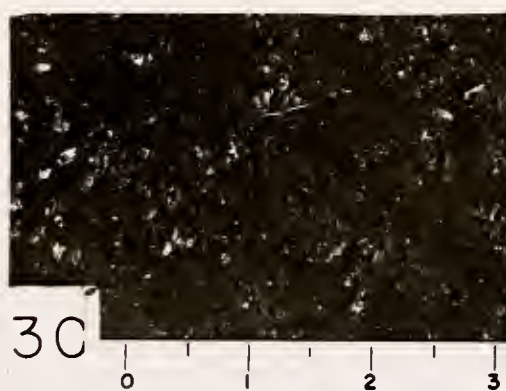
C. ASPHALTIC CONCRETE
GRAVEL



D. SURFACE TREATMENT
GRAVEL

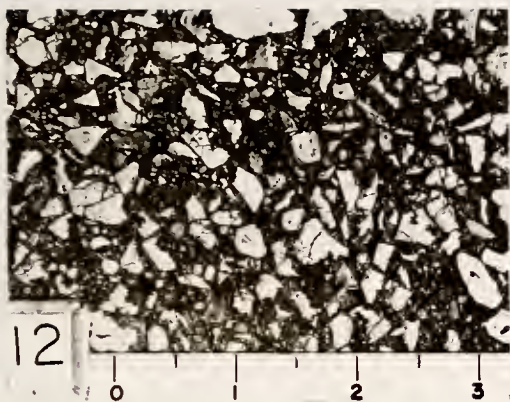


E. KENTUCKY ROCK
ASPHALT SURFACE

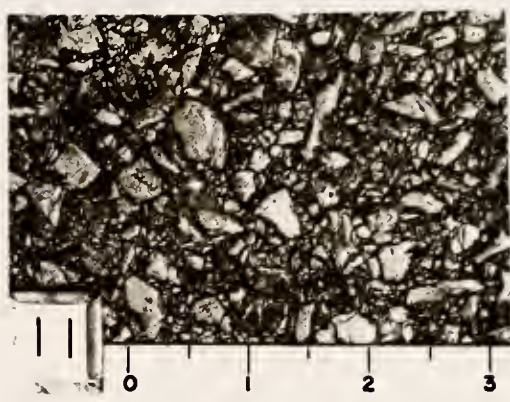


F. "BLEEDING" ASPHALT
SURFACE

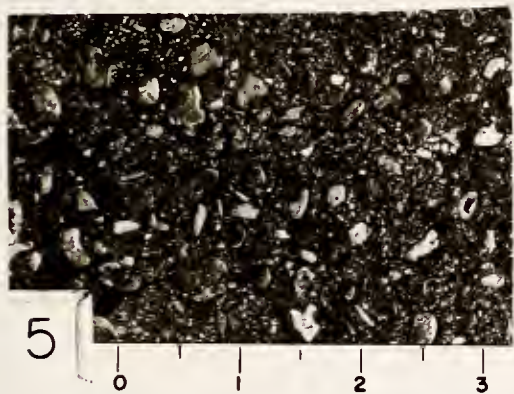
FIG. II REPRESENTATIVE SURFACES OF
THE HIGHWAY TEST SECTIONS



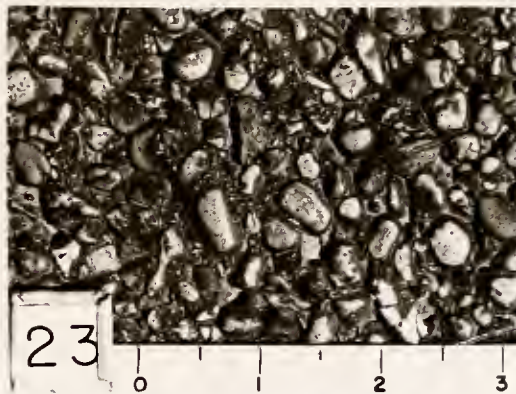
A. ASPHALTIC CONCRETE
LIMESTONE



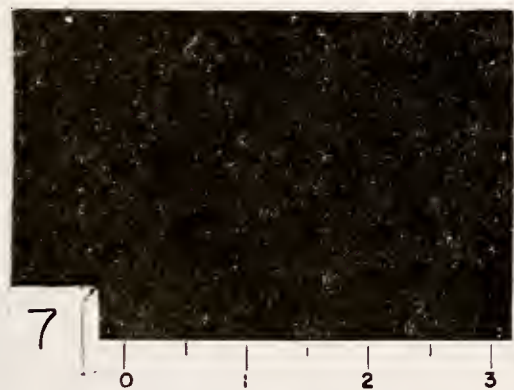
B. SURFACE TREATMENT
LIMESTONE



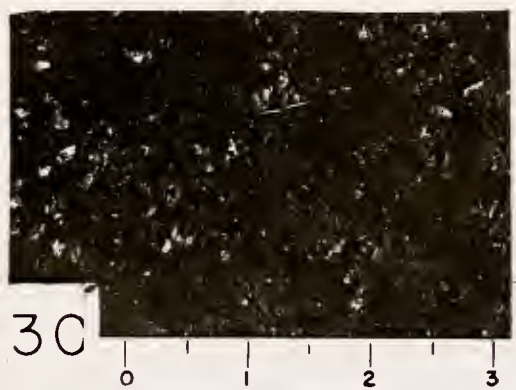
C. ASPHALTIC CONCRETE
GRAVEL



D. SURFACE TREATMENT
GRAVEL



E. KENTUCKY ROCK
ASPHALT SURFACE



F. "BLEEDING" ASPHALT
SURFACE

FIG. II REPRESENTATIVE SURFACES OF
THE HIGHWAY TEST SECTIONS

textured, as illustrated in Figure 11(e). Test sections 7, 8, and 24 are Kentucky rock asphalt surfaces.

Test section 30 is a "bleeding" asphalt surface located on a secondary county road. Figure 11(f) is a photograph of this surface.

Discussion of Field Correlation Results

The results for the 18 surfaces on which both stopping-distance measurements and laboratory resistance values were obtained are listed in Table 1. The stopping distances for the other 14 surfaces are not included, since they contributed nothing to the correlation study. Information listed in this table includes the test section number, to aid in associating Figures 11(a) through (f) with their appropriate section, and a general surface type classification.

For each of these sections stopping distance measurements and relative resistance values are given. The average figures listed in both cases are the arithmetic means of three skids, with the maximum and minimum values also listed to indicate the variability encountered on each of the test surfaces. The stopping-distance measurements are given in feet while the laboratory relative resistance values are dimensionless, but based on a relative resistance value of unity for a Kentucky rock asphalt specimen.

It was impossible to obtain an accurate stopping-distance measurement on test section 30. On each of five

TABLE 1

Summary of Field and Laboratory Skid-Test Results

Test Section	Surface Type	<u>Stopping Distance in Feet</u>			<u>Relative Resistance Value</u>		
		Average	Maximum	Minimum	Average	Maximum	Minimum
1	G-ST	89.5	90.5	88.5	.59	.60	.58
3	G-AC	99.8	102.0	97.6	.66	.67	.65
4	L-ST	92.5	93.0	92.0	.57	.60	.55
5	G-AC	118.5	120.5	116.5	.63	.65	.62
6	G-AC	83.0	83.5	82.5	.75	.75	.74
7	KRA	69.3	70.0	68.0	.99	1.01	.97
8	KRA	62.2	63.2	63.0	1.06	1.09	1.04
9	L-AC	138.0	140.5	135.0	.45	.45	.44
11	L-ST	153.0	153.5	152.5	.35	.36	.33
12	L-AC	85.3	86.1	84.6	.63	.64	.62
13	L-AC	125.3	126.0	124.0	.53	.55	.50
14	L-ST	172.0	176.0	168.0	.34	.35	.34
16	G-ST	103.5	104.0	102.5	.58	.60	.57
23	G-ST	102.0	102.0	102.0	.55	.56	.54
24	KRA	62.0	62.0	62.0	1.01	1.02	.99
26	L-ST	97.7	98.5	96.5	.60	.62	.58
27	G-ST	93.7	96.5	91.0	.57	.60	.54
30	"Bleeding" Asphalt	Greater than 150 feet			.23	.28	.17

Surface Type Identification:

L-AC Limestone - Asphaltic Concrete
 L-ST Limestone - Surface Treatment
 G-AC Gravel - Asphaltic Concrete
 G-ST Gravel - Surface Treatment
 KRA Kentucky Rock Asphalt

attempts the rear end of the test vehicle gradually slid toward the ditch, so that after skidding approximately 150 feet the right rear wheel struck the shoulder and dug in, causing the vehicle to tip appreciably. As a result, about all that can be indicated for the stopping distance on this surface is that it is somewhat "greater than 150 feet", as listed in Table 1.

Figure 12 shows the comparison between the field and laboratory methods of determining the skidding resistance of bituminous surfaces. Results are plotted for only 15 of the test sections so that an equal number of each of the first five general surface types illustrated by Figure 11 would be represented. It was impossible to plot the results for the "bleeding" asphalt section, since no adequate stopping distance measurements were available.

In order to select a curve that represented the best relationship between the 15 plotted points, a second degree regression curve was computed. However, this curve deviated appreciably from the plotted points at the maximum and minimum values, and it was felt that a visual interpretation would give a better indication of the relationship between the two methods. Therefore, the solid curve of Figure 12 was drawn in by eye.

It was anticipated in the planning phase of the correlation study that a linear correlation might exist between the field and laboratory methods of determining skidding

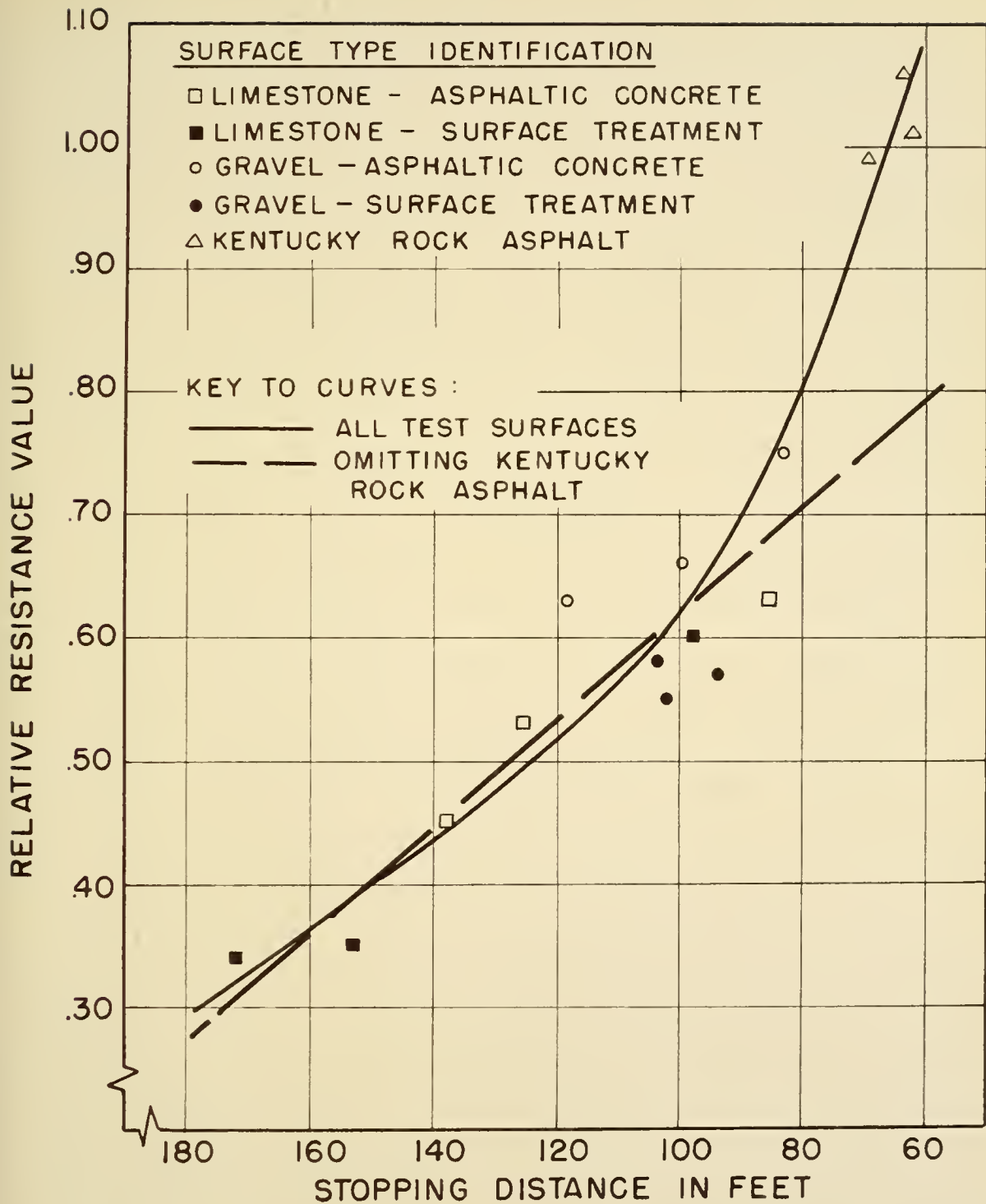


FIG.12 COMPARISON BETWEEN FIELD AND LABORATORY SKID-TEST MEASUREMENTS

resistance. Examination of the plotted points indicated that with the exception of the Kentucky rock asphalt specimens, all of the points did conform fairly closely to a linear plot. Since there was some justification for omitting the Kentucky rock asphalt surfaces in this analysis, as will be discussed later, a correlation analysis was performed on the 12 remaining test surfaces and resulted in a linear correlation coefficient of 0.96, as computed by the method of least squares. The broken line in Figure 12 represents the linear correlation curve for these 12 surfaces.

An examination of the location of the plotted points with respect to the linear correlation line showed that certain surface types consistently fell either entirely above or entirely below the correlation line. This lack of randomness in the location of the plotted points indicated that there was some discrepancy between the field and laboratory methods of evaluation.

Consideration of the test results, in conjunction with a close examination of the test specimens, showed where this discrepancy lay. For surfaces of medium texture there was good agreement in the relative skidding resistance as determined by the two methods. For very open-textured surfaces, however, the laboratory method indicated relatively poorer anti-skid characteristics than did the stopping-distance method. Conversely, for an extremely dense surface

the laboratory method showed relatively higher resistance values than were obtained by field measurements.

This relationship is illustrated in Figure 12 by the location of points corresponding to three different surface types. The very dense Kentucky rock asphalt specimens are all grouped appreciably above the linear correlation line. Similarly the gravel asphaltic concrete surfaces which were quite dense, as shown in Figure 11(c) also plotted above the correlation line. However, the open-textured gravel surface treatments, as typified by Figure 11(d), resulted in values which fell below the correlation line. The limestone specimens, for the most part, exhibited a medium texture and did not consistently deviate from the linear correlation curve.

Two of the possible reasons why a difference in surface texture caused a discrepancy between the field and laboratory methods for evaluating the relative skidding resistance of bituminous surfaces pertain to the amount of water present on the surface during testing and to the occurrence of a film of oil and dust on the highway test surfaces. The degree of saturation of the test surface was probably the more significant of the two causes. In the laboratory method the rate of water application was constant for all specimens, and occurred simultaneously with the test itself, so that the surface was thoroughly drenched during actual testing.

In the stopping distance method, however, there was an appreciable time lapse between the application of the water and the performance of the skidding test. On very dense surfaces the rate at which water drained from the surface was slow, and the test section remained in a drenched condition for some little time. On the open-textured test sections, however, the surface did not remain drenched, particularly when the pavement temperature was well over 100 F., as was the case for the majority of the testing program. It was impossible to maintain a continuous water film on these coarse-textured pavements, and the water quickly evaporated from the tops of the projecting aggregate. As a result, there was not complete consistency in the degree of saturation of the pavement test surfaces. This would tend to result in relatively higher skidding-resistance values for open-textured surface types than for dense surfaces, when evaluated by the field stopping-distance method.

The second possible source of difference was the presence of the film of oil drippings, worn rubber, and dust on the highway during testing. Previous research (10, 25) has noted this film as a factor contributing to the so-called seasonal effect, since it is more pronounced during the summer months. It has also been noted that a dense surface is more sensitive to the seasonal effect than an open-textured one. During the coring operation, in which the abrasive

and ground-up aggregate swirled around on the surface of the core, and subsequent cleaning of the test specimen, prior to testing, this seasonal film was removed. This resulted in the laboratory test method indicating a relatively higher skidding resistance for a dense surface than for an open-textured surface, as compared to the field method.

A final factor to be considered, which would apply to the Kentucky rock asphalt specimens only, is that previous research (22) has shown that this type of surface possesses nearly uniform high anti-skid characteristics for all speed ranges. The majority of the surface types, however, exhibit a marked decrease in resistance as speed increases (10, 25). The stopping-distance method measures a resistance value which represents an integrated average of the total resistance developed, as the vehicle is skidding from the speed at which the brakes are applied down to zero speed. The laboratory method, on the other hand, evaluates the resistance at a constant speed.

The stopping-distance method, therefore, for a surface which exhibits uniform anti-skid resistance for all speed ranges, would give an evaluation of the skidding resistance which would be the same for all speeds, and this value should conform fairly closely to the resistance as determined by the laboratory method. For a surface type which shows higher skidding resistance at the lower speed ranges,

however, the stopping-distance method, since it reflects the frictional force being developed over the entire speed range, would indicate that the surface exhibits better skidding resistance than would the laboratory method, which evaluates the specimen at high speed only.

As a result, the stopping-distance method measures a relatively higher skidding resistance than the laboratory method for surfaces which exhibit a decrease in skidding resistance with speed, while the laboratory method indicates a relatively higher resistance for the Kentucky rock asphalt surfaces which possess uniform skidding resistance at all speed ranges. This is illustrated in Figure 12 by the marked deviation of the points corresponding to the three Kentucky rock asphalt surfaces from the linear correlation line.

After considering the results of this correlation study, it was decided that the laboratory skid-test apparatus would be entirely satisfactory for a laboratory investigation of factors affecting the skidding resistance of bituminous paving mixtures. Although some discrepancy exists between results obtained by the field and laboratory methods, it was felt that the factors contributing to this discrepancy tended to favor the laboratory method as giving a more realistic evaluation of the skidding resistance of a wet pavement surface for speeds of 30 mph and upward. The laboratory method would probably have shown closer agreement

with the truck-trailer method of determining skidding resistance on the highway, since both of these methods evaluate the test surfaces at a constant speed. Unfortunately, equipment of this nature was not available for the correlation study.

PREPARATION OF THE STANDARD LABORATORY SPECIMEN

The primary consideration in the molding of the laboratory test specimens was to arrive at a surface condition which was representative of the texture that a similar mix would exhibit on a highway surface. Although the specimen had to possess sufficient surface durability to prevent disintegration under the severe action of the wearing procedure, stability and density, as such, were not considered important to this study, and no measurements of these properties were made.

The following procedure refers to the standard laboratory specimen on which the majority of the research program was based. Any deviation from this standard procedure is included with the discussion of that particular phase of the research to which the deviation applies.

Although the aggregate gradation for a standard specimen is included in this section, a description of the aggregates themselves is presented with the results. Over 25 natural and artificial aggregates were used in this study, and grouping the aggregate descriptions with the results facilitates a comparison of the various aggregate types with their respective resistances to polishing.

Materials

An 85-100 penetration grade asphalt cement furnished by The Texas Company from the Port Neches refinery was used for all of the test specimens molded in the laboratory. Standard test results for this asphalt are listed in Table 2.

The asphalt content selected for the standard laboratory specimen was 4.5 percent, based on the total weight of the bituminous mixture. In arriving at this selected value, mixes ranging in asphalt content from 3.5 to 6.5 percent were investigated, with the 4.5 percent figure representing the best compromise. It seemed desirable to keep the mix as lean as possible in order to prevent the asphalt from flushing to the surface during the wearing procedure and obscuring the polishing characteristics of the aggregate, while too low an asphalt content resulted in a mixture which exhibited poor surface stability during the severe wearing procedure.

The bituminous-concrete mixture chosen for the standard laboratory specimen conformed to the specifications of the State Highway Department of Indiana for Hot Asphaltic Concrete - Type B (Medium Texture), except for the asphalt content, which was kept low as explained above. Table 3 lists the specification limits, adjusted to conform to the sieve series used in this investigation, and the selected composition for the standard specimen. Figure 13 shows a

TABLE 2

Results of Standard Tests on Asphalt Cement

Test	Result
Specific Gravity; 77/77 F.	1.010
Softening Point, Ring and Ball; F.	118
Ductility; cm.	200+
Penetration; 100 grams, 5 seconds, 77 F.	93
Penetration; 100 grams, 5 seconds, 32 F.	28
Flash Point, Cleveland Open Cup; F.	565
Loss on Heating; 50 grams, 5 hours, 325 F., percent.	0.03
Penetration on Residue; 77 F., percent of original.	91
Solubility in Carbon Tetrachloride; percent.	99.86
Oliensis Spot Test.	Negative

TABLE 3

Indiana Specification Limits for Hot Asphaltic Concrete-Type B
and
Mixture Composition Used for Standard Laboratory Specimens

Passing Sieve	Retained on Sieve	Type B Limits in Percent		Selected Composition in Percent
		Minimum	Maximum	
1/2 inch	3/8 inch	2	14	12
3/8 inch	No. 4	20	50	36
No. 4	No. 8	0	22	10
No. 8	No. 16	5	20	11
No. 16	No. 30	5	13	12
No. 30	No. 50	5	12	11
No. 50	No. 100	2	17	3
No. 100	No. 200	1	5	2
No. 200	—	3	5	3
Bitumen (Percent of total weight)		6.5	8.5	4.5

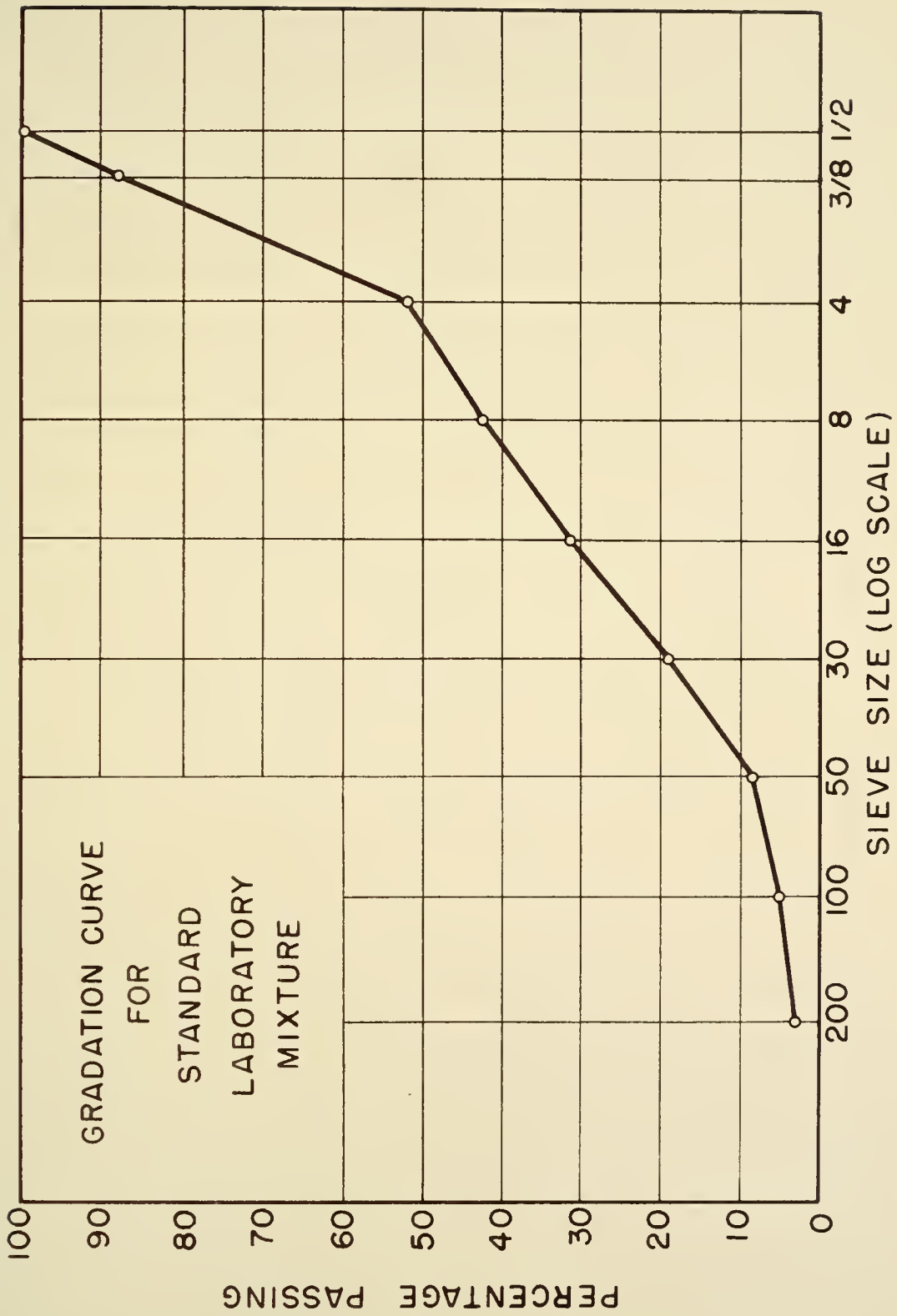


FIG. 13

plot of the aggregate grading listed in the right-hand column of Table 3.

In establishing this gradation as the standard composition, preliminary tests were performed on a wide variety of mixtures ranging in texture from a very dense mix, with the gradation conforming to Fuller's maximum density curve, to an extremely open one which was essentially a one particle size mixture. The asphaltic concrete Type B mixture appeared to give the most satisfactory surface texture and degree of coarse aggregate exposure of any of the mixtures tested. Subsequent results, presented in a separate section, consider the effects of texture and gradation on the skidding resistance of bituminous paving mixtures.

Batching, Mixing, and Molding Procedure

Most of the mineral aggregates used in this study were received in a crushed condition with the coarse and fine aggregate fractions combined. A few ledge samples were obtained, and these were reduced to suitable sizes in a DFC No. 2 Crusher, made by the Denver Fire Clay Company, and an Iler Improved Grinder of the Fen Machine Company, Cleveland, Ohio. In order to achieve a high degree of control over the aggregate gradation, the mineral aggregates were first separated into the various sieve size

fractions, after which they were recombined in the desired proportions.

For most of the specimens, a 2000-gram sample of aggregate resulted in a bituminous mixture which was sufficient for filling the 6-inch diameter specimen to a compacted depth of 2 inches. However, on some of the very harsh angular aggregates, which were difficult to compact, this value had to be reduced to 1900 grams to keep from overflowing the mold. Three test specimens were made for each mixture, and three different mixtures were molded and tested at a time, giving a total of nine specimens for each series.

A complete mixing and molding procedure for a standard laboratory test specimen consisted of the following steps:

1. The batched sample of aggregate and the asphalt cement were placed in separate containers in a Peerless gas oven and brought up to a temperature of 300 ± 10 F. A short time prior to mixing, the molds, mixing bowl, paddle, etc., were also placed in the oven.

2. When the materials reached the proper temperature, the heated flat-bottomed mixing bowl was placed on a beam balance and was tared. The aggregate was then placed in the bowl and its weight determined to the nearest gram which provided a check on the batching operation. A weight equivalent to the amount of asphalt cement to be incorporated into the mixture was added to the beam, and the hot

asphalt was then poured into the bowl until the beam again balanced.

3. The mixing bowl was next placed on the Hobard electric mixer and the aggregate and asphalt mixed together for 2 minutes with the equipment operating at slow speed.

4. The mixture was then transferred with a large metal spoon to the test specimen mold, which was fitted with a collar to confine the uncompacted mix. All metal parts which came into contact with the mixture were heated prior to contact.

5. The surface of the mixture was smoothed with the metal spoon and a 1/2-inch thick circular steel plate, having a diameter 1/8 of an inch smaller than the inside diameter of the mold, was then placed directly on the surface. The mixture was vibrated for one minute with a Cleveland pneumatic vibrator, as illustrated in Figure 14. On the left side of this figure is shown a specimen being vibrated with the collar, bearing plate, bearing block, and vibrator in place, and, on the right, a completed specimen.

6. At the completion of the vibration the specimen was permitted to cool at room temperature for 30 minutes at which time it was placed in an oven, maintained at 140 F., for an additional 30 minutes.

The specimen was then ready for the first rolling process of the wear and polishing procedure, which is described in a previous section.

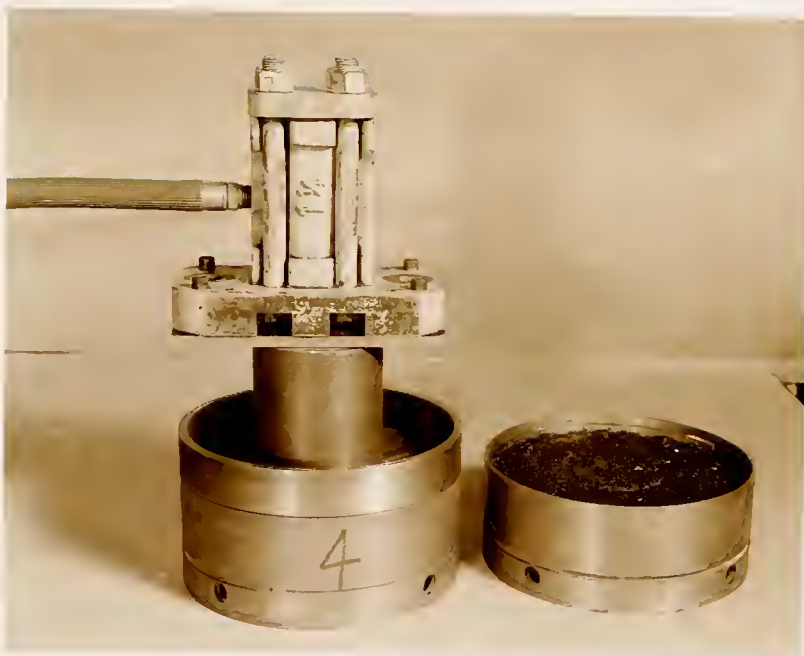


Figure 14. Laboratory Vibration Equipment and Compacted Test Specimen

THE EFFECT OF THE TYPE OF AGGREGATE
ON THE SKIDDING RESISTANCE OF BITUMINOUS MIXTURES

The dominant variable affecting the resistance of a well-designed bituminous pavement to the polishing effect of traffic is the type of aggregate used in the mixture. The skidding resistance of the surface during any phase of the polishing cycle is dependent, to a large extent, upon the type of aggregate used in the mixture, with the influence of the type of aggregate becoming more pronounced as polishing progresses.

In the laboratory study of this phase of the investigation, the skidding characteristics of bituminous mixtures made with 22 different mineral aggregates were evaluated. In choosing the aggregates to be included, an effort was made to obtain a representative selection of the most common types of crushed stone used in bituminous paving construction. Nine of the aggregates were from Indiana, eight from Virginia, three from Kansas, and one each from Maryland and Massachusetts.

Twelve of the 22 aggregates were limestone. This type of aggregate has a reputation for polishing, and a fairly complete coverage seemed justified.

Only two of the aggregates were gravels and both of these were rather uniform high-quartz aggregates. This represents a disproportionately small number of gravels when considering the tremendous quantity of this material that is used in bituminous paving construction throughout the United States. However, it was felt that gravels, due to their lack of homogeneity, would not be as well suited to the purposes of this study as uniform crushed stone sources. Although it is possible to evaluate the polishing characteristics of a given gravel, it is difficult to relate these results to any basic characteristics of the heterogeneous aggregate, or to predict the behavior of other gravel sources.

Included in this section, and in related Appendix B, are a petrographic description and a list of results of the standard physical tests for each of the 22 aggregates. A partial chemical analysis is also listed for the twelve limestones. Lastly, the results of skidding tests on bituminous mixtures made with each of these aggregates are tabulated, and a discussion relating the skidding results to the basic properties of the aggregates is presented.

Description of the Aggregates

The results of the physical tests on the 22 mineral aggregates are listed in Table 4. The specific gravity and absorption determinations were made in accordance with the standard AASHTO test, T85-45, while the Los Angeles abrasion test conformed to T96-49, Test Grading B. The data for the physical tests were all obtained by laboratory technicians of the Joint Highway Research Project, except for the Los Angeles abrasion results on the eight Virginia aggregates. Due to the lack of material conforming to Grading B for these eight aggregates, the values determined by the Virginia Department of Highways were accepted and are listed in Table 4.

There was a high degree of uniformity in the apparent specific gravity of the limestones, with nine of the values grouped between 2.71 and 2.74, and the other three ranging from 2.68 to 2.83. Absorption values varied from 0.38 to 4.20 percent, and abrasion loss from 16.2 to 32.8 percent.

The ten other aggregate types exhibited a high degree of variability, which was to be expected, since a wide diversity of aggregate types was represented. Apparent specific gravity varied from a low of 2.64 for chert up to 3.04 for the dense diabase. Absorption values ranged from 0.03 percent for rhyolite to 11.16 percent for one of the sandstones. Loss on abrasion increased from a low of 12.0

TABLE 4

Results of Physical Tests on the Mineral Aggregates

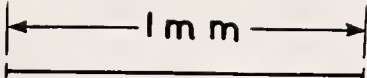
Aggregate Identifica- tion Symbol	General Classifi- cation	<u>Specific Gravity</u>		Absorption	L.A. Abra- sion Loss Percent
		Bulk	Apparent	Percent	
L-1	Limestone	2.66	2.71	0.63	23.7
L-2	Limestone	2.43	2.71	4.20	25.9
L-3	Limestone	2.56	2.74	2.61	32.9
L-4	Limestone	2.45	2.68	3.45	30.3
L-5	Limestone	2.48	2.71	3.55	27.4
L-6	Limestone	2.57	2.72	2.10	30.4
L-7	Limestone	2.70	2.73	0.38	30.6
L-8	Limestone	2.73	2.76	0.38	18.1
L-9	Limestone	2.77	2.83	0.78	16.2
L-10	Limestone	2.71	2.74	0.43	18.4
L-11	Limestone	2.63	2.71	1.11	26.2
L-12	Limestone	2.63	2.71	1.06	32.8
C-1	Chert	2.52	2.64	1.72	18.8
R-1	Rhyolite	2.68	2.68	0.03	14.2
Q-1	High Quartz Gravel	2.65	2.67	0.31	39.4
Q-2	High Quartz Gravel	2.59	2.65	0.88	35.2
S-1	Sandstone	2.64	2.68	0.57	28.5
S-2	Sandstone	2.05	2.66	11.16	98.3
D-1	Diabase	2.92	3.01	0.98	17.8
D-2	Diabase	2.93	3.04	1.31	12.0
G-1	Granite	2.79	2.83	0.53	26.8
SL-1	Slag	2.34	2.65	5.03	35.7

percent for a diabase to over 98 percent for the same sandstone which exhibited high absorption.

A petrographic description of each of the 22 aggregates is listed in Appendix B. The petrographic work was performed with the assistance of Dr. R. W. Lounsbury, Head of the Geology Division of the School of Civil Engineering of Purdue University. Included with each of the petrographic descriptions is an identification symbol (conforming to those of Table 4), a location by state as to the source of the aggregate, and a megascopic description. The petrographic identification does not, in all cases, agree with the general classification of the aggregates listed in Table 4. This general classification is the "popular" description by which the aggregate is known in its respective locality.

Photomicrographs of thin sections of ten typical aggregates are illustrated in Figures 15 and 16. Six of the twelve limestones are represented in Figure 15, and indicate the wide variety of grain size and shape that is encountered under the general category of limestone. Figure 16 illustrates four of the other aggregate types. These photomicrographs are considered more fully in a subsequent discussion of the results of the skidding tests.

A partial chemical analysis was performed on the twelve limestones, under the direction of Dr. W. L. Dolch of the Joint Highway Research Project staff, with the

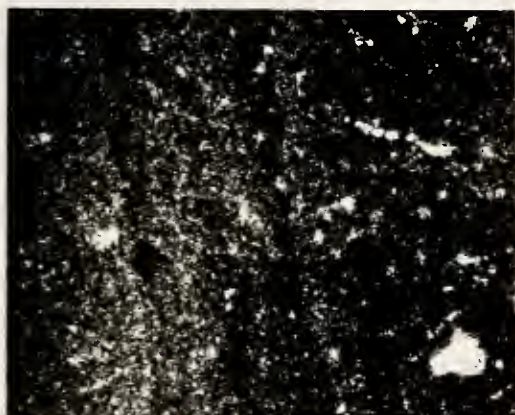
SCALE: 



L-1



L-2



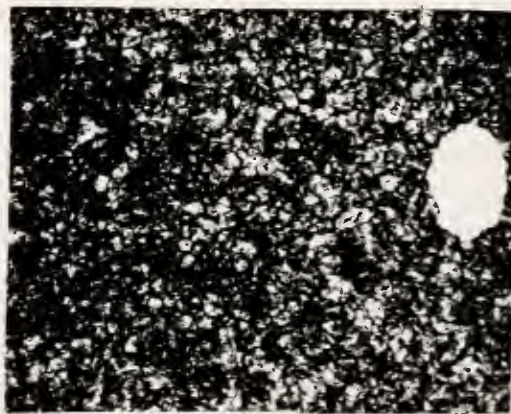
L-7



L-3



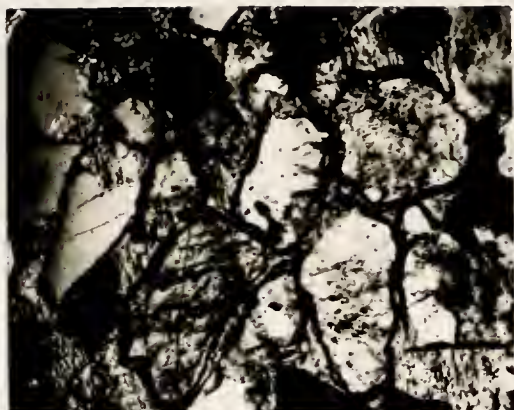
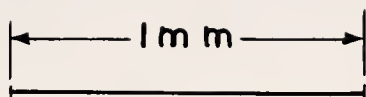
L-11



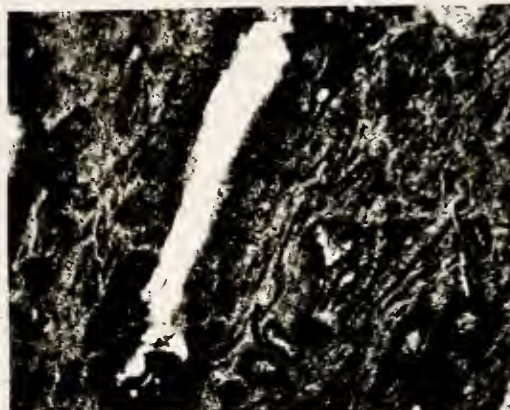
L-4

FIG.15 PHOTOMICROGRAPHS OF
LIMESTONE THIN SECTIONS

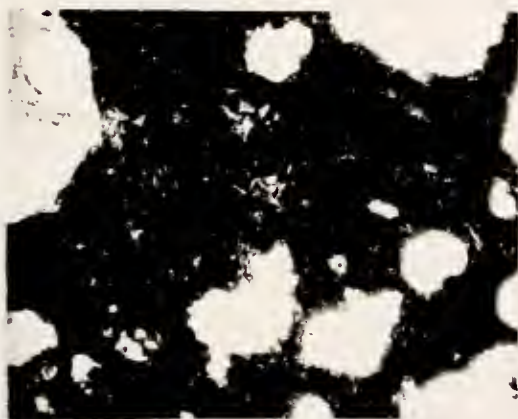
SCALE:



S - 2



R - 1



SL - 1



D - 1

FIG.16 PHOTOMICROGRAPHS OF THIN
SECTIONS OF "RESISTANT" AGGREGATE

results listed in Table 5. Percentages of three of the major constituents are tabulated; calcium as CaCO_3 , magnesium as MgCO_3 , and silica as SiO_2 . The sum of these three constituents doesn't necessarily total one hundred percent. There may be some other material, such as iron or alumina, present; or portions of the tabulated constituents may exist in some other chemical form, so that the sum, as computed on the basis of the given assumptions, may total over one hundred percent.

Some of the limestones are almost pure calcium carbonate, with L-11 indicating 98.5 percent CaCO_3 . Other limestones are more dolomitic, with L-4 consisting of 39.9 percent magnesium carbonate. The chemical composition also is discussed more fully in a subsequent section.

Discussion of Testing Procedure

Laboratory skid-test measurements were obtained on bituminous mixtures made from each of the 22 mineral aggregates. Three test specimens were made for each aggregate type and skidding-resistance determinations were performed on each of the test specimens at the completion of the initial-rolling, the coarse-wear, and the fine-polish cycles.

Only one of the three specimens was subjected to the final rolling procedure and the related test. As previously indicated, this operation coats the aggregate

TABLE 5

A Partial Chemical Analysis of the Twelve Limestones
Included in the Program of Research

Aggregate Identification Symbol	Calcium as CaCO_3 Percent	Magnesium as MgCO_3 Percent	Silica as SiO_2 Percent	Total of the Three Compounds Percent
L-1	94.9	0.5	3.5	98.9
L-2	58.0	38.4	4.4	100.8
L-3	60.8	34.9	2.1	97.8
L-4	54.7	39.9	4.3	98.9
L-5	66.8	24.9	5.8	97.5
L-6	83.1	5.1	4.3	92.5
L-7	93.5	1.7	2.9	98.1
L-8	74.1	8.3	7.0	89.4
L-9	54.3	27.1	3.1	84.5
L-10	86.7	4.6	5.6	96.9
L-11	98.5	0.8	1.3	100.6
L-12	95.1	0.3	3.3	98.7

particles with a light film of asphalt and is intended to simulate the seasonal effect. However, this procedure is not completely realistic, and it was felt that the results at the completion of the fine-polish cycle were the most significant with regard to indicating the resistance of a bituminous mixture to polishing.

The bituminous mixture used for the standard test specimen was a fairly open-graded asphaltic concrete with the aggregate gradation conforming to that of Table 3, and containing 4.53 percent asphalt based on the weight of the mixture. All specimens were made in accordance with the standard procedure, previously described, with the following exceptions:

1. The asphalt content on the soft sandstone (S-1) was increased to 4.8 percent, and on the vesicular slag (SL-1) to 5.2 percent. The bituminous mixtures containing these two aggregates were extremely dry when the normal 4.53 percent asphalt was added, and it was necessary to increase the asphalt content to arrive at a mixture comparable in appearance to that of the other aggregate types.

2. One of the limestones received from Virginia (L-7) was deficient in the 1/2 to 3/8-inch material, so one-half of this coarse fraction was replaced by 3/8-inch to No. 4 material.

3. All of the mineral aggregates were crushed except Q-2, which was a natural high-quartz gravel.

4. Some of the bituminous mixtures made with certain aggregates exhibited poor resistance to the combined hydraulic and scouring action experienced during the 10-minute cycle in the Minitrack. In order to keep the surface from completely disintegrating without adding more asphalt or an anti-stripping agent, the length of the cycle was decreased from 10 minutes down to from 4 to 7 minutes on the following aggregates: R-1, C-1, and D-1. Since this operation was primarily one of eroding away the matrix surrounding the coarse aggregate, and not a polishing action, this deviation should not have resulted in an appreciable variation in the final results.

Results of the Laboratory Skid Tests

The results of skidding tests on bituminous mixtures made with the 22 mineral aggregates are listed in Table 6. Relative resistance values are tabulated for each of the test specimens with an average, or arithmetic mean, listed for each series of three similar specimens that received identical wear. There was excellent consistency between results from the specimens for a given test series, particularly after an appreciable amount of wear. At the completion of the fine-polish cycle, the maximum deviation of an individual test value from any of the respective means was only 0.02.

TABLE 6

Summary of Results on the Polishing of Bituminous Mixtures
Containing Different Types of Aggregate

Aggregate Identification Symbol	Specimen No.	RRV at the Completion of:			
		Initial Rolling	Coarse Wear	Fine Polish	Final Rolling
L-1	1	.53	.43	.35	.33
	2	.54	.44	.37	
	3	.55	.45	.38	
	Avg.	<u>.54</u>	<u>.44</u>	<u>.37</u>	
L-2	1	.69	.57	.53	.47
	2	.72	.62	.54	
	3	.70	.60	.54	
	Avg.	<u>.70</u>	<u>.60</u>	<u>.54</u>	
L-3	1	.70	.58	.52	.46
	2	.70	.59	.50	
	3	.71	.60	.51	
	Avg.	<u>.70</u>	<u>.59</u>	<u>.51</u>	
L-4	1	.75	.64	.56	.50
	2	.74	.63	.56	
	3	.76	.62	.56	
	Avg.	<u>.75</u>	<u>.63</u>	<u>.56</u>	
L-5	1	.72	.59	.51	.41
	2	.72	.59	.51	
	3	.68	.57	.49	
	Avg.	<u>.71</u>	<u>.58</u>	<u>.50</u>	
L-6	1	.61	.50	.45	.41
	2	.59	.50	.44	
	3	.59	.50	.45	
	Avg.	<u>.60</u>	<u>.50</u>	<u>.45</u>	
L-7	1	.51	.44	.30	.30
	2	.49	.44	.32	
	3	.50	.43	.33	
	Avg.	<u>.50</u>	<u>.44</u>	<u>.32</u>	
L-8	1	.56	.49	.45	.37
	2	.56	.50	.47	
	3	.56	.50	.47	
	Avg.	<u>.56</u>	<u>.50</u>	<u>.46</u>	

TABLE 6 (continued)

Aggregate	Specimen	Initial Rolling	Coarse Wear	Fine Polish	Final Rolling
L-9	1	.58	.52	.50	.39
	2	.57	.50	.48	
	3	.58	.50	.47	
	Avg.	<u>.58</u>	<u>.51</u>	<u>.48</u>	
L-10	1	.56	.46	.42	.33
	2	.56	.47	.43	
	3	.56	.48	.44	
	Avg.	<u>.56</u>	<u>.47</u>	<u>.43</u>	
L-11	1	.55	.41	.34	.29
	2	.54	.42	.35	
	3	.53	.40	.33	
	Avg.	<u>.54</u>	<u>.41</u>	<u>.34</u>	
L-12	1	.56	.48	.46	.38
	2	.57	.49	.45	
	3	.58	.49	.46	
	Avg.	<u>.57</u>	<u>.49</u>	<u>.46</u>	
C-1	1	.73	.63	.55	.48
	2	.73	.63	.55	
	3	.72	.62	.55	
	Avg.	<u>.73</u>	<u>.63</u>	<u>.55</u>	
R-1	1	.68	.59	.55	.48
	2	.68	.60	.56	
	3	.70	.62	.59	
	Avg.	<u>.69</u>	<u>.60</u>	<u>.57</u>	
Q-1	1	.72	.64	.62	.57
	2	.69	.66	.63	
	3	.70	.66	.63	
	Avg.	<u>.70</u>	<u>.65</u>	<u>.63</u>	
Q-2	1	.57	.53	.52	.47
	2	.56	.53	.52	
	3	.60	.57	.53	
	Avg.	<u>.58</u>	<u>.54</u>	<u>.52</u>	
S-1	1	.94	.88	.88	.85
	2	.95	.90	.88	
	3	.98	.90	.89	
	Avg.	<u>.96</u>	<u>.89</u>	<u>.88</u>	

TABLE 6 (continued)

Aggregate	Specimen	Initial Rolling	Coarse Wear	Fine Polish	Finel Rolling
S-2	1	.79	.76	.74	
	2	.76	.76	.74	.67
	3	.75	.76	.76	
	Avg.	<u>.77</u>	<u>.76</u>	<u>.75</u>	
D-1	1	.81	.66	.62	.51
	2	.79	.67	.63	
	3	.77	.64	.62	
	Avg.	<u>.79</u>	<u>.66</u>	<u>.62</u>	
D-2	1	.84	.68	.59	
	2	.80	.67	.58	.50
	3	.80	.64	.58	
	Avg.	<u>.81</u>	<u>.66</u>	<u>.58</u>	
G-1	1	.68	.63	.65	
	2	.69	.62	.63	
	3	.70	.62	.65	.56
	Avg.	<u>.69</u>	<u>.62</u>	<u>.64</u>	
SL-1	1	.82	.67	.60	
	2	.78	.64	.59	
	3	.80	.66	.59	.54
	Avg.	<u>.80</u>	<u>.66</u>	<u>.59</u>	

Figure 17 compares the average relative resistance values at the completion of the fine-polish cycle for test specimens made with the 22 mineral aggregates. Results for the twelve limestone aggregates are plotted on the left of the figure and indicate an over-all average of 0.45, with a range of from 0.32 to 0.56. Relative resistant values for the other ten aggregates are illustrated on the right side of Figure 17. They resulted in an over-all average of 0.63, with a range of from 0.52 to 0.88.

The progressive decrease in skidding resistance due to wear and polish is illustrated in Figure 18 for bituminous mixtures made with three different aggregate types. The initial test for each of the three specimens was taken immediately following the vibration procedure and before any rolling of the specimen in the Minitrack took place. This is not a point normally included in the standard procedure, but does indicate the skidding resistance of a test surface before any particle orientation due to the rolling action occurs. The other four points correspond, respectively, to tests following initial rolling, coarse wear, fine polish, and final rolling.

As illustrated in Figure 18, a bituminous mixture containing sandstone exhibits excellent resistance to polishing; one with rhyolite has a fair amount of resistance; but a bituminous mixture made with oolitic limestone shows very little resistance to polishing and may become dangerously slippery.

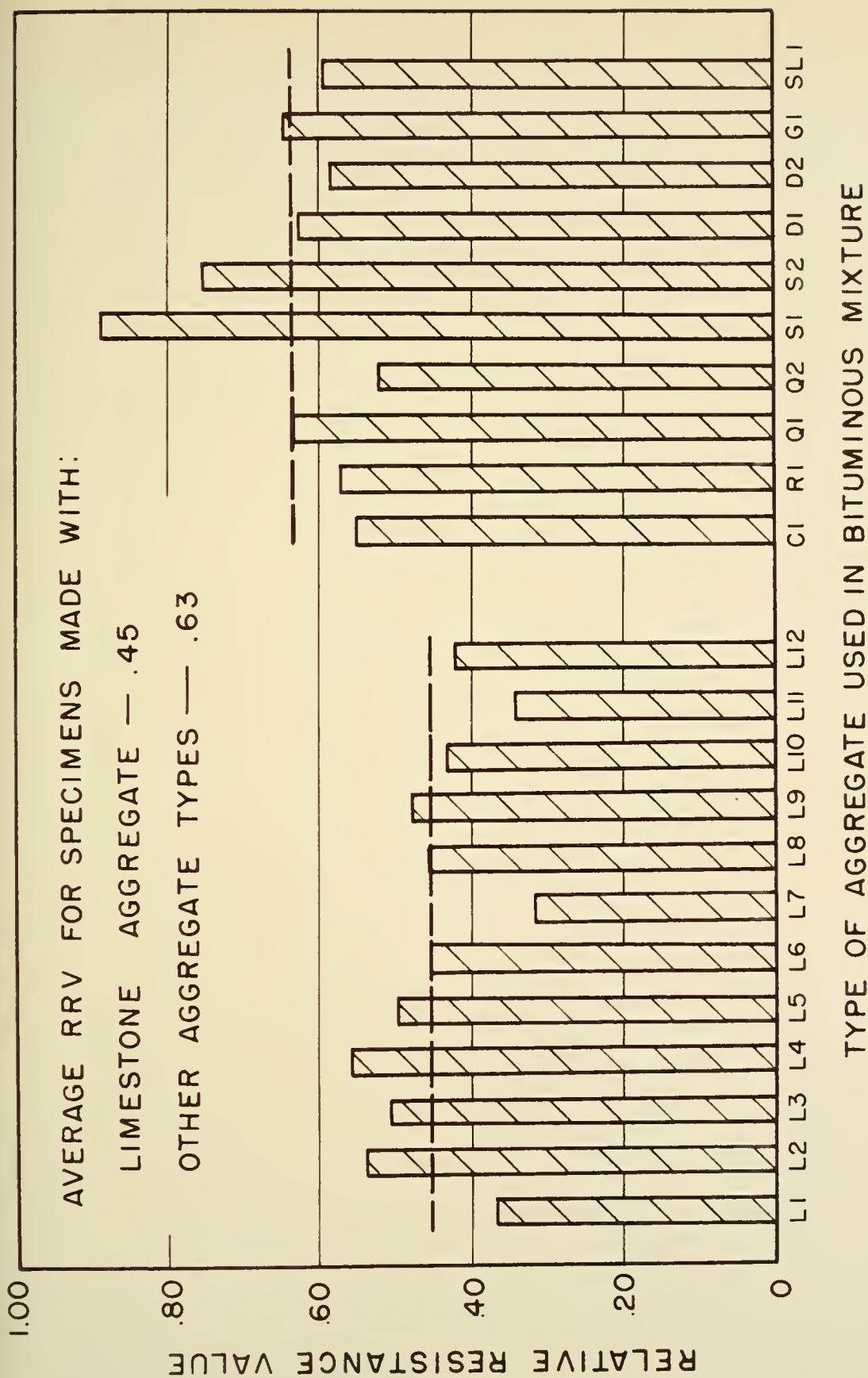


FIG.17 SKIDDING RESISTANCE OF BITUMINOUS MIXTURES AT
THE COMPLETION OF THE FINE POLISH CYCLE

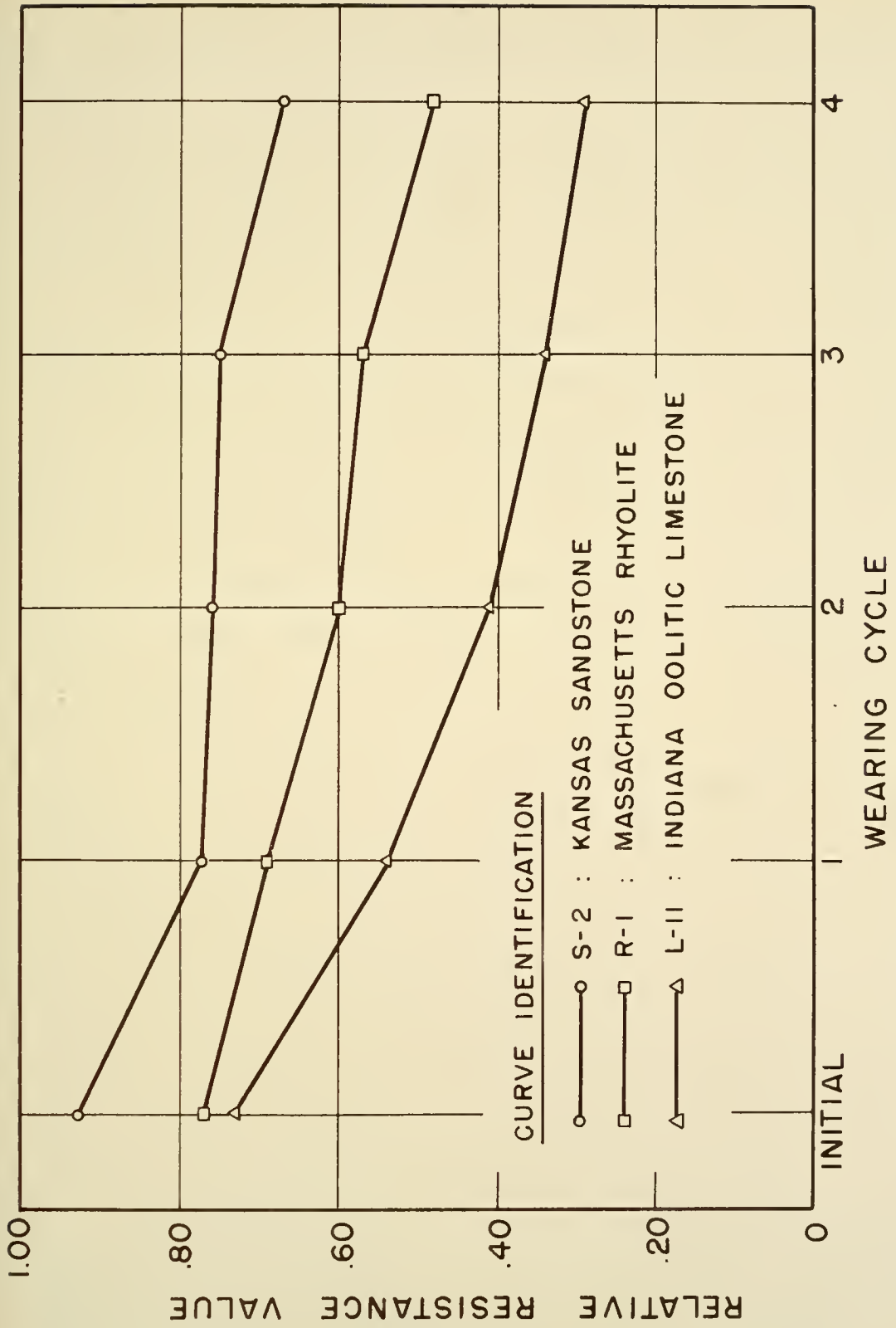


FIG.18 VARIATION IN SKID RESISTANCE OF BITUMINOUS MIXTURES WITH WEAR

Discussion of the Skid Test Results

An examination of the test results leads to three pertinent conclusions:

1. Limestone aggregates, as a group, exhibit poorer anti-skid characteristics in bituminous mixtures than the other aggregate types tested.
2. There is an appreciable difference in the resistance to polishing between different limestones.
3. A sandstone aggregate exhibits by far the best anti-skid characteristics of any of the aggregate types evaluated in this study.

The following discussion will amplify and endeavor to explain these results in terms of the basic properties of the aggregates.

Unfortunately, there appears to be no relationship between any of the standard physical tests and the anti-skid characteristics of an aggregate. These tests are relatively simple to perform and a significant correlation with the absorption or loss on abrasion, for example, would be fortuitous. However, a comparison of the results of the physical tests in Table 4 with the relative resistance values of Table 6 fails to develop any correlation, even within a given aggregate type such as limestone.

The petrographic descriptions of the various aggregates provide a somewhat more fruitful source of information for relating aggregate properties and anti-skid

characteristics. Reference will be made to the photomicrographs of Figures 15 and 16 in this comparison.

The photomicrographs in the left column of Figure 15 represent the three aggregates which exhibited the poorest anti-skid characteristics. At the completion of the fine polish cycle the relative resistance values for L-1, L-7, and L-11 were 0.37, 0.32, and 0.34, respectively. L-7, which gave the lowest skidding resistance of any of the 22 aggregates, was a very uniform fine-grained limestone with the subangular calcite grains averaging less than 0.01 mm in length. These soft calcite grains wore away very readily where the unit pressure between the polishing shoe and aggregate was high, and there resulted a uniformly polished level datum which was extremely slippery when wet.

The next most slippery aggregate was L-11. As illustrated in Figure 15, the structure of this limestone is completely dissimilar to that of L-7. It consists of large spherical to ovate oolites, averaging 0.4 to 0.5 mm in length, bound in a granular matrix of calcite. However, as there was no angularity to the individual oolites, and since the hardness of the oolites and the surrounding matrix was essentially the same, the nature of the wear was very uniform, resulting in a polished surface. To a lesser degree this same condition also existed for L-1.

The three photomicrographs in the right column of Figure 15 represent the limestones which exhibited the best

anti-skid resistance. At the completion of the fine-polish cycle the relative resistance values for L-2, L-3, and L-4 were 0.54, 0.51, and 0.56, respectively. L-4, which gave the best results, was a crystalline granular limestone with interlocking grains, 0.02 to 0.06 mm in length. The granular interlock promoted greater resistance to wear, so that the initial angularity of the aggregate particles was maintained for a greater period than for limestone L-7. The individual grains were also somewhat larger and more angular than for L-7, so the resulting surface was not as uniformly polished. In addition, there was some porosity in L-4 which helped to relieve the excess pressure set up in the water film, resulting in a high unit pressure between testing shoe and specimen.

Limestone L-3 was quite similar to L-4, as indicated by the respective photomicrographs, but it had less porosity than L-4; and, consequently, did not possess as much skidding resistance. L-2, on the other hand, probably owed its relatively high skidding resistance to the presence of the coarse calcite rhombs. The fine ground mass was quite similar to that of L-7, but the larger calcite rhombs disturbed the continuity and prohibited a uniformly polished surface from existing.

The photomicrographs of Figure 16 illustrate structures common to other aggregate types. SL-1 was a vesicular slag with a small amount of silicate microlites. The

voids in the glassy structure probably relieved the excess hydraulic pressure, and eliminated an unbroken polished surface, so that the RRV at the end of the fine-polish cycle was 0.59.

The popular classification of R-1 is a rhyolite, or, as identified by Dr. Lounsbury, a porphyritic dacite. The ground mass was very fine-grained, but the monotony of the structure was relieved by large feldspar phenocrysts. This aggregate had an RRV of 0.57 at the end of the fine-polish cycle, placing it about equal in resistance to polishing to the most resistant limestone evaluated in this study.

The dolerite, of which photomicrograph D-1 is an example, consisted of coarse grains averaging over 1 mm in length. The resistant labradorite and augite grains maintained an appreciable amount of the initial aggregate angularity, and the RRV at the completion of the fine-polish cycle was 0.62.

The photomicrograph for the sandstone, S-2, illustrates the type of structure that is necessary to provide permanent resistance to the polishing effects of traffic. This was a calcareous sandstone in which the quartz grains were bound in a matrix of calcite. The quartz particles were very resistant, having a relative hardness of seven, while the cementing calcite was comparatively weak, with a hardness of three. The matrix wore away at a fast rate,

exposing the hard quartz particles and promoting excellent skidding characteristics.

In addition, the nature of the wear of S-2 also contributed to good skidding resistance. The surrounding matrix eventually wore down to the point where it could no longer support each quartz particle, so rather than remaining indefinitely exposed to the polishing action of traffic, after an appreciable period of wear the particle was ejected from the surface of the specimen. This continuous ejection of worn quartz grains, and the resulting exposure of fresh harsh particles, caused a constant rejuvenation of the surface. The RRV for S-2 decreased only 0.02, from 0.77 to 0.75, during the entire wear and polish procedure.

This type of wear and surface rejuvenation is similar to that experienced by the dense Kentucky rock asphalt and silica sand surfaces, which also exhibit excellent skidding characteristics. Unless this coarse, particle-by-particle wearing phenomenon does occur, ultimate polishing will result. After extreme polishing action, bituminous test specimens made both with rhyolite, R-1, and a high-quartz gravel, Q-1, exhibited relative resistance values below 0.40.

Other information which provided a basis of comparison of the resistance to polishing of the twelve different limestones was the chemical analysis data, listed in Table 5. There appeared to be a good correlation between the calcium

carbonate content of a limestone and its susceptibility to polishing. This relationship is illustrated in Figure 19, and results in a correlation coefficient, as determined by the method of least squares, of 0.96.

There is some intuitive justification for this relationship. In discussing the skidding resistance of the various aggregate types with respect to their petrographic descriptions and photomicrographs, it was emphasized that a lack of consistency of structure or of grain hardness appeared to be essential for good skidding resistance. The more nearly a limestone approaches to pure calcium carbonate, the more uniform and continuous would be the structure and hardness, so that the resistance to polishing would be low.

For the twelve limestones included in this testing program the primary "impurity" was magnesium carbonate. As a result, on the basis of this study it might appear that dolomitic limestones exhibit better anti-skid characteristics than high-calcium limestones because of their high magnesium content. However, the correlation coefficient relating the percent of magnesium with the skidding resistance was 0.84, or slightly less than the correlation coefficient for calcium carbonate. Consequently, the results seem to indicate that rather than a high magnesium content contributing to anti-skid resistance, any "impurity", which tends to disturb the continuity of the pure calcium

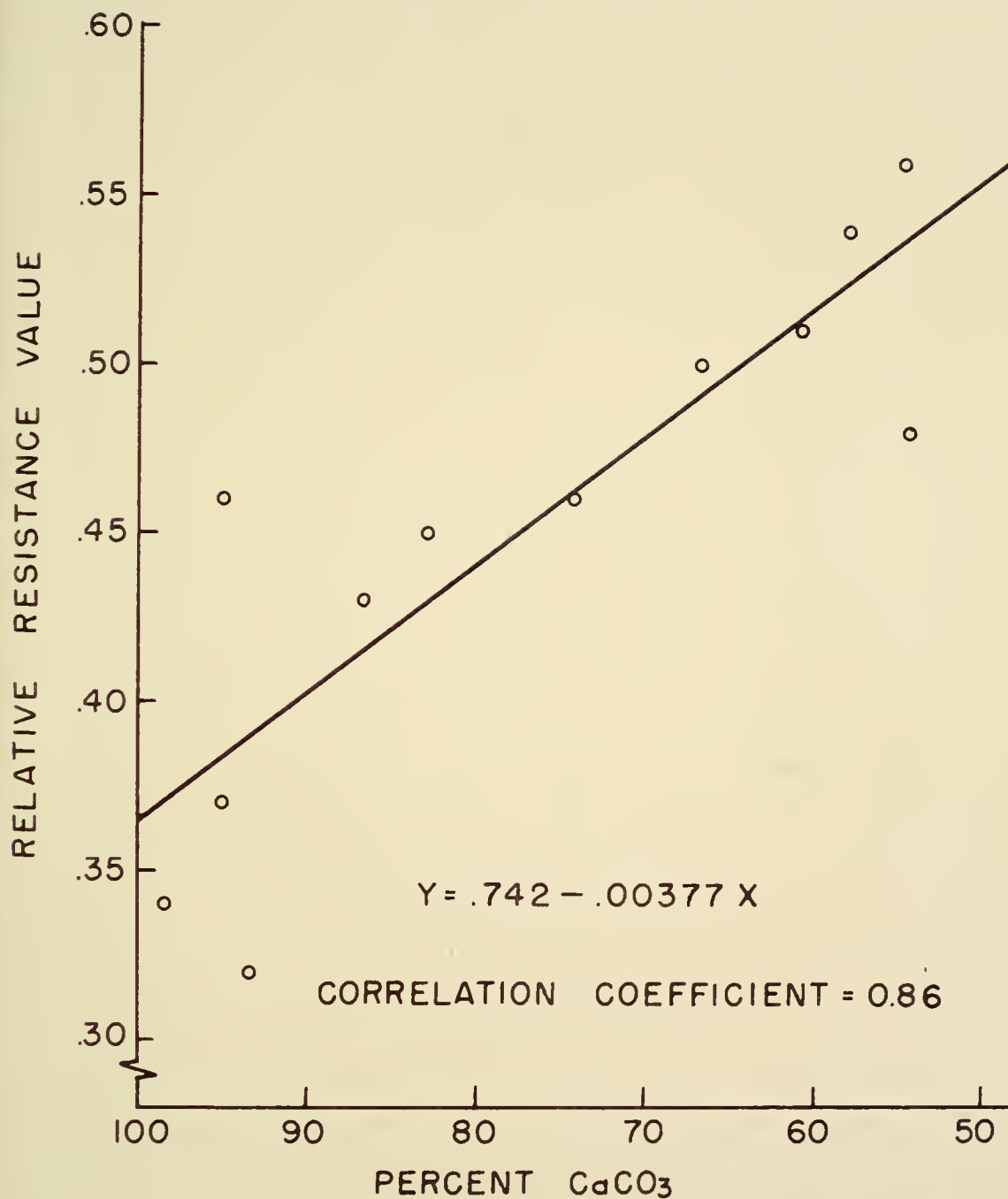


FIG. 19 CORRELATION BETWEEN CaCO_3 CONTENT
AND POLISHING SUSCEPTIBILITY

carbonate grains, will result in some improvement in the skidding resistance of the limestone.

THE EFFECT OF SURFACE TEXTURE AND AGGREGATE
SHAPE ON PAVEMENT SLIPPERINESS

In studying the effect of the different aggregate types, all of the mixes were made to conform to a standard gradation; and the aggregates, except for Q-2, were completely crushed. To provide a better understanding of other variables affecting skidding resistance of bituminous mixtures, four of the representative aggregates were selected for additional study with regard to the effect of surface texture* and initial aggregate particle shape. Two of these aggregates were limestones; one, a dolomitic limestone (L-4), that had exhibited good skidding resistance, and the other, an oolitic limestone (L-11), which had shown very little resistance to polishing. The other two aggregate types were a rhyolite (R-1) and a sandstone (S-2).

An examination of the data listed in Table 6 indicates that a high degree of consistency was obtained for each series of three test specimens. At the completion of the fine-polish cycle, test results for the 22 different aggregates showed that four series exhibited maximum deviations of 0.02 from the average value, 16 had deviations of only 0.01, and two of the test series had identical results for all three of the test specimens. This indicates that the

* Refer to "TERMINOLOGY", page xii.

use of a single specimen should give results that are nearly as significant as those obtained on a series of three specimens, and would accomplish a tremendous saving in material, time, and effort. Consequently, the testing program for this and subsequent sections utilized one test specimen for each specific test condition, rather than three.

Included in this section are descriptions of the test procedures and a discussion of results pertaining both to the effect of surface texture and to the effect of initial particle shape.

Surface Texture Investigation

The surface texture of the four most open-textured specimens was varied by adjusting the gradation. The maximum aggregate size for each of these four mixtures was 1/2-inch. The specimen conforming to Gradation No. 5 consisted of aggregate which passed the No. 4 sieve. The mixture composition of each of the five specimens is presented in Table No. 7. Gradation No. 3 was the standard laboratory mixture and is representative of an Indiana asphaltic concrete, AH Type B.

Gradation No. 1 was the most open-textured and was a mixture of 40 percent of Indiana Specification size No. 9 coarse aggregate and 60 percent size No. 12 coarse aggregate.

TABLE 7

Composition of Specimens for Surface Texture Study

Passing Sieve	Retained Sieve	Gradation Number				
		1	2	3*	4	5
1/2 inch	3/8 inch	27.0	19.2	12.0	8.0	0
3/8 inch	No. 4	32.0	34.1	36.0	19.0	0
No. 4	8	29.2	19.1	10.0	14.0	19.2
8	16	4.7	8.0	11.0	11.0	15.1
16	30	3.8	7.9	12.0	10.0	14.0
30	50	3.3	7.5	11.0	10.0	13.3
50	100	0	1.6	3.0	11.0	15.1
100	200	0	1.0	2.0	10.0	13.7
200	Pan	<u>0</u>	<u>1.6</u>	<u>3.0</u>	<u>7.0</u>	<u>9.6</u>
		100.0	100.0	100.0	100.0	100.0

Aggregate

Asphalt content in percent of
total weight of mixture

L-4 and L-11	3.5	4.0	4.5	5.2	5.7
R-1 and S-2	3.0	3.5	4.5	5.0	5.4

* Standard Test Specimen

The second mixture had a gradation which fell approximately midway between that of No. 1 and 3.

Gradation No. 4 conformed to that of a standard surface mixture with 1/2-inch maximum size aggregate of the U. S. Army Corps of Engineers. Gradation No. 5 was similar, except that all of the aggregate passed a No. 4 sieve.

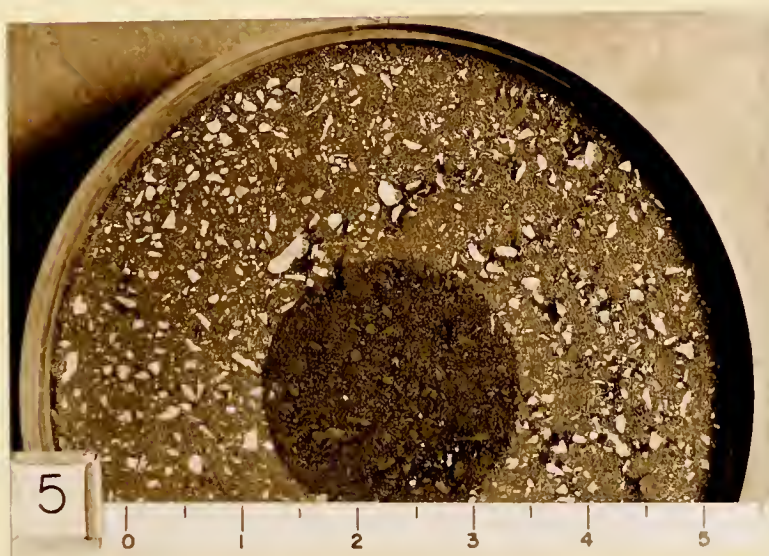
Figure 20 represents the surface textures of Gradations No. 1 and No. 5, and illustrates, respectively, the most open-textured and the most dense-textured specimens included in this investigation. These photographs were taken at the completion of the coarse-wear cycle.

The skidding resistance values for specimens tested in the surface-texture study are listed in Table 8, and are shown graphically in Figures 21(a) and 21(b). The open-textured specimens of Gradation No. 1 exhibited very poor resistance to the wearing and polishing procedure, and none of the four No. 1 specimens satisfactorily completed the entire cycle without disintegrating.

Figure 21(a) illustrates the results for the two limestones and clearly indicates that the denser surface textures exhibit better resistance to skidding than do the more open mixtures at all stages of wear and polish. There is as much as 0.16 difference between the RRV for the most open- and most dense-textured mixtures of L-4, which was a dolomitic limestone. The difference was smaller for L-11, an oolitic limestone, but still was an appreciable amount.



a. Gradation No. 1; Most Open Texture.



b. Gradation No. 5; Most Dense Texture.

Figure 20. Surface Texture of Test Specimens

TABLE 8
Relative Resistance Values for the
Surface Texture Study

Aggregate Wear and Polish Cycle	Gradation Number				
	1	2	3*	4	5
<u>L-4</u>					
After initial rolling	.64	.66	.75	.76	.80
After coarse wear	.55	.59	.63	.64	.68
After fine polish	X	.50	.56	.60	.65
<u>L-11</u>					
After initial rolling	.49	.52	.54	.56	.60
After coarse wear	.38	.40	.41	.45	.48
After fine polish	X	.34	.34	.38	.42
<u>R-1</u>					
After initial rolling	.63	.65	.69	.75	.80
After coarse wear	X	.56	.60	.67	.72
After fine polish	X	.56	.57	.59	.60
<u>S-2</u>					
After initial rolling	.73	.76	.77	.78	.82
After coarse wear	.69	.74	.76	.78	.86
After fine polish	X	.73	.75	.80	.86

* Tabulated values for Gradation No. 3 are the average values from Table 6 for the respective aggregate type.

X Specimen collapsed during some phase of the wearing, polishing, or testing cycles.

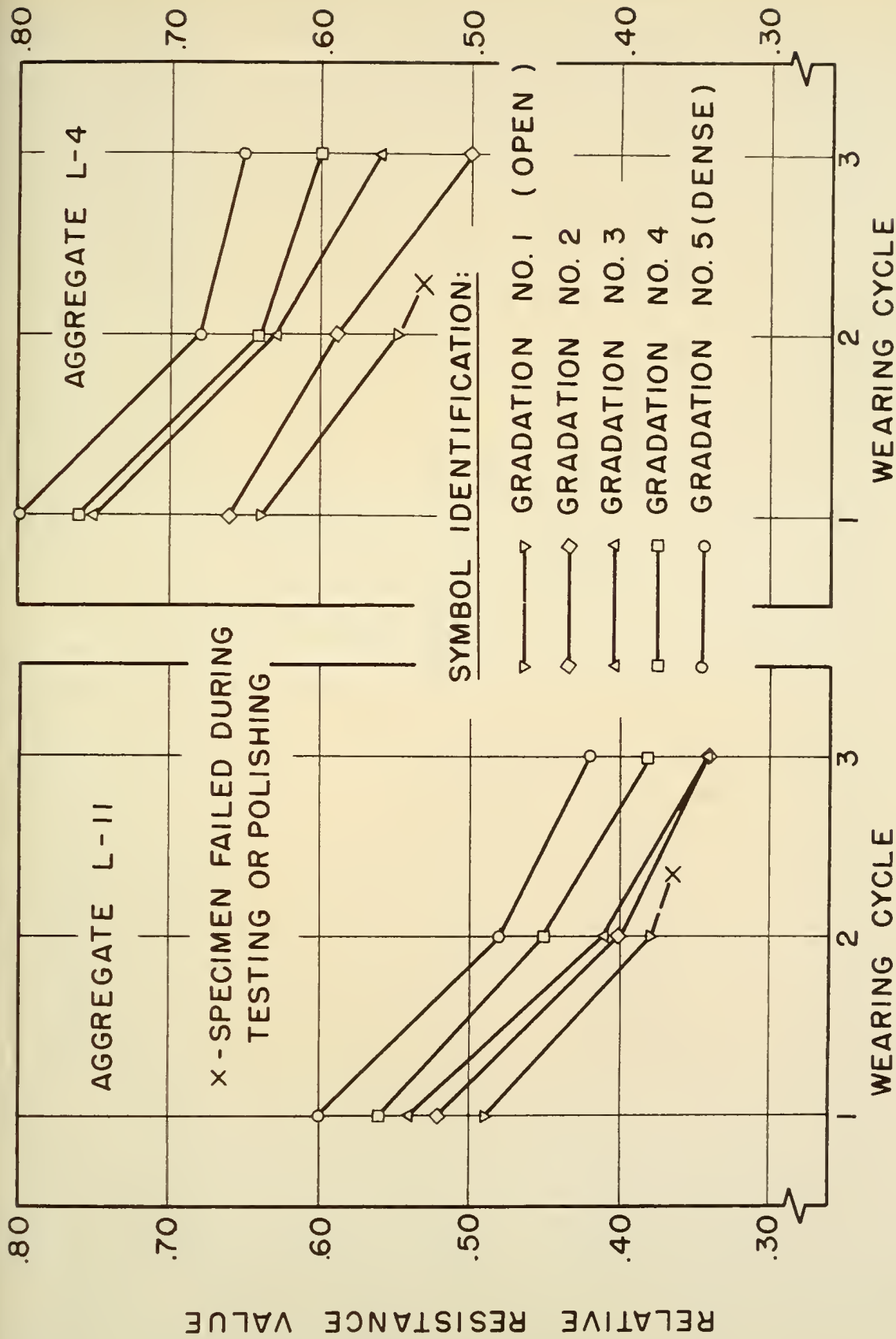


FIG. 21a EFFECT OF SURFACE TEXTURE ON THE POLISHING CHARACTERISTICS OF BITUMINOUS MIXTURES

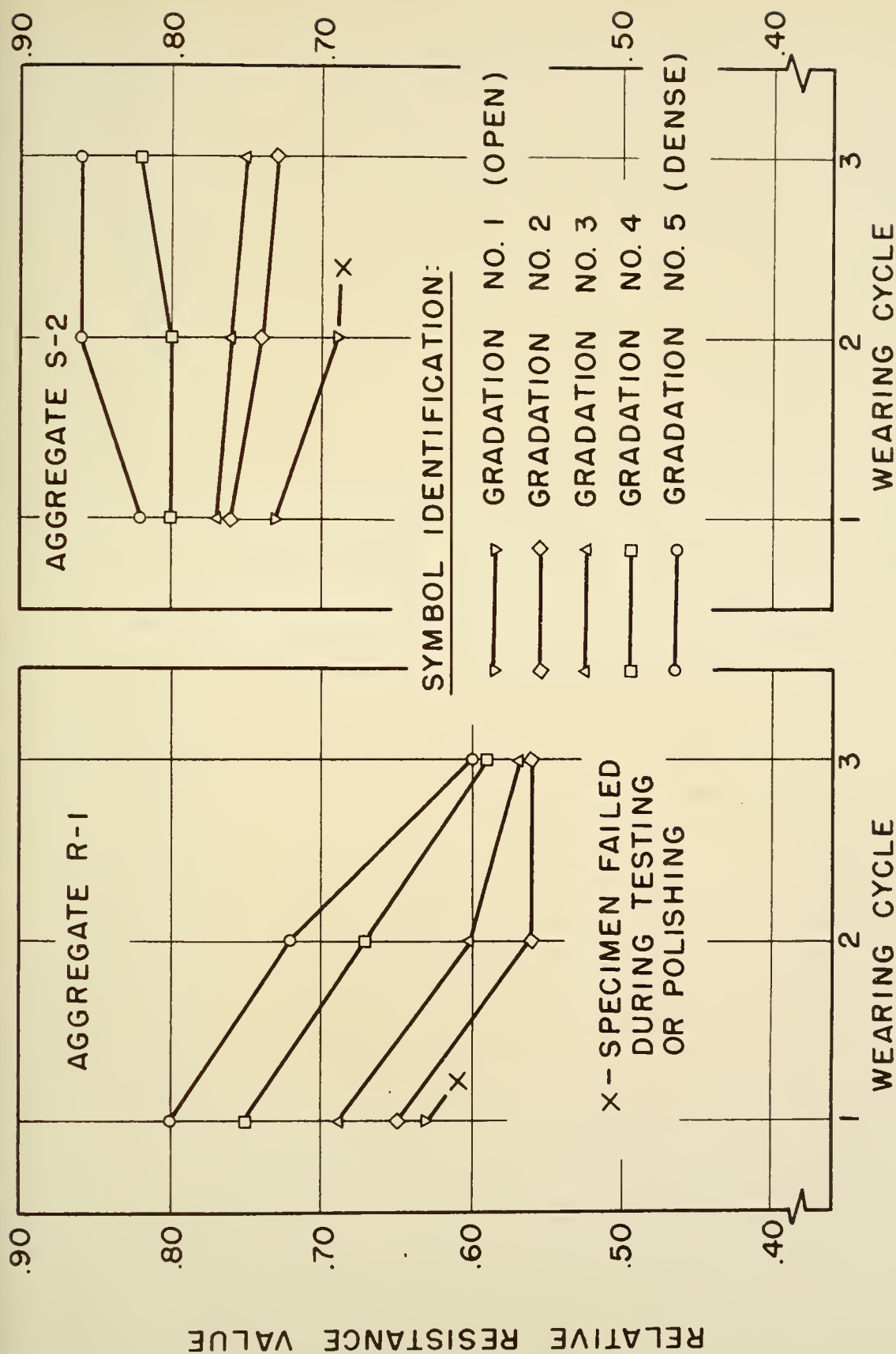


FIG. 21b EFFECT OF SURFACE TEXTURE ON THE POLISHING CHARACTERISTICS OF BITUMINOUS MIXTURES

Similarly, as shown in Figure 21(b), the denser rhyolite and sandstone surfaces gave better anti-skid characteristics than the open-graded mixtures.

For the sandstone, S-2, wear and polish improved the skidding resistance of the two most-dense specimens. By scraping off the asphalt coating, which accumulated on the aggregate during mixing, and eroding away some of the fine aggregate and asphalt matrix, the coarse aggregate became more prominent than it was in the initial condition. This resulted in a higher skidding resistance as the wear and polishing procedure progressed.

The results obtained by varying surface texture with the four different aggregates are summarized in Figure 22. This figure shows the relative resistance values at the completion of the fine-polish cycle for Gradation No. 5, the most dense-textured specimen, and for Gradation No. 2, the most-open mixture which satisfactorily completed the wear and polish procedure. Although the texture effect is not as significant as the difference between the various aggregate types, in all four cases the dense-textured specimens exhibit appreciably higher resistance to skidding than do the open-textured specimens.

In considering that these data conclusively indicate that, for a given aggregate, a dense surface can develop higher anti-skid resistance than an open-textured surface, two qualifying observations should be made:

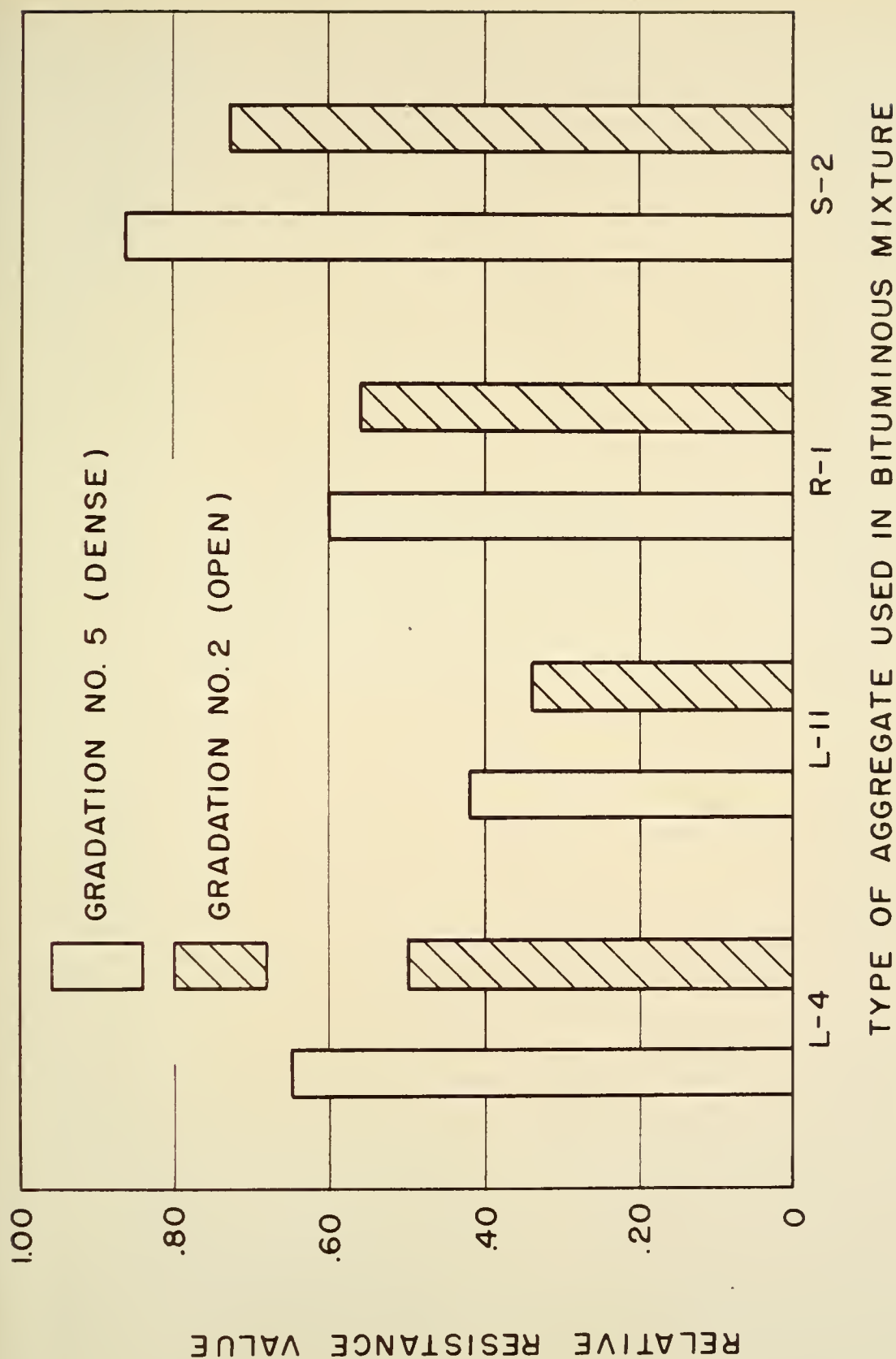


FIG.22 COMPARISON OF THE RESISTANCE TO POLISHING OF DENSE AND OPEN TEXTURED BITUMINOUS MIXTURES

The first is that these mixtures were intentionally kept quite lean, as the asphalt contents of Table 7 indicate. In no case was an excess of asphalt noted during any portion of the wearing and testing procedure for any of the test specimens. From the practical standpoint, asphalt contents are generally higher than those used in this study. With some rich mixtures the additional consolidation, due to the action of traffic after the pavement has been placed, will result in a "fat", slick surface. An open-graded mixture, with a relatively high void content, can accommodate a higher amount of densification than a dense mixture without resulting in a surface that is flushed with asphalt.

The other factor which should be considered is that in the laboratory testing procedure the test specimen was thoroughly drenched, and the degree of saturation of the surface was not a function of the surface texture of the specimen. On the highway, however, the rate of drainage from the surface is dependent upon the texture; and, as noted in the field testing program it was extremely difficult to thoroughly drench some of the open-textured surfaces.

Therefore, the previous conclusion that, for a given aggregate, a dense mixture will possess better anti-skid resistance than an open-graded mixture, would apply only if there was no excess asphalt at the pavement surface and if the pavement were well-drenched. If either of these conditions did not exist, particularly if the dense surface was

flushed with asphalt, the reverse of the conclusion could apply.

Particle Shape Investigation

To investigate the effect of the initial aggregate shape on the skidding characteristics of bituminous mixtures, the same four aggregates that were included in the texture study were used, i.e., L-4, L-11, R-1, and S-2. In the standard tests, for which the results are listed in Table 6, the mixtures made with each of these aggregates consisted entirely of freshly-crushed material.

To provide a basis of comparison as to particle shape, a separate sample of each of these aggregates was placed in a Los Angeles abrasion machine for four hours. No steel balls were used, and the wearing action of aggregate on aggregate and against the shell of the machine caused the individual particles to become quite rounded.

The resulting material was then sieved, batched, and mixed in accordance with the standard procedure. The finished specimen was identical to the corresponding standard specimen, except that whereas the standard specimen contained aggregate which was freshly crushed, the modified specimen consisted entirely of artificially rounded aggregate particles.

The relative resistance values of the two types of specimens are plotted in Figure 23 for the four different

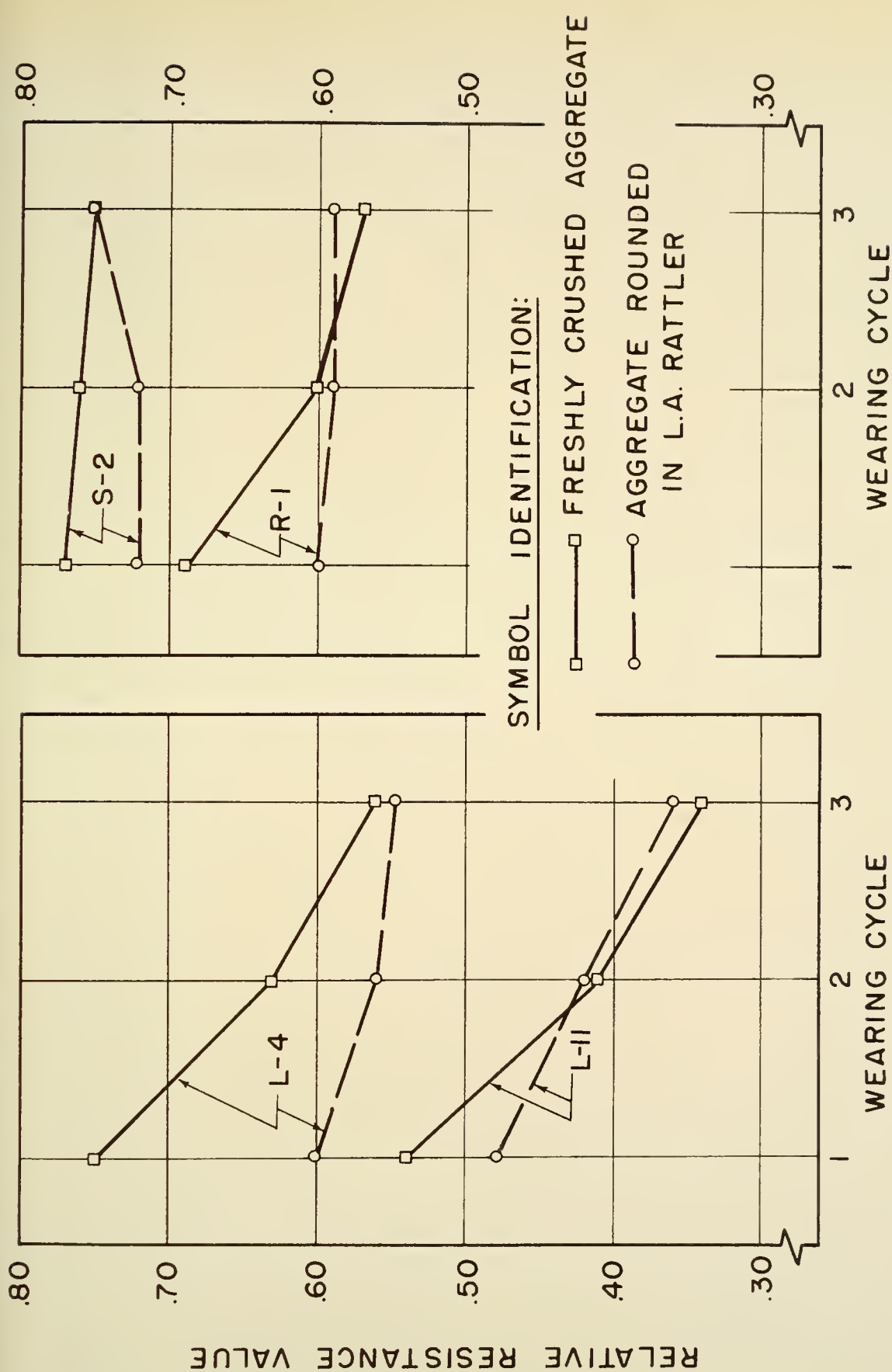


FIG. 23 EFFECT OF AGGREGATE SHAPE ON THE POLISHING CHARACTERISTICS OF BITUMINOUS MIXTURES

aggregates. The initial RRV's for specimens made from all four of the aggregates were higher for the angular than for the rounded-aggregate, as was to be expected. After an appreciable amount of wear, however, as represented at the completion of the fine-polish cycle (Wearing Cycle No. 3), this advantage had disappeared. For two of the aggregates the specimens made with rounded particles gave slightly superior final results, while the specimen containing angular aggregate showed up better than the corresponding rounded-aggregate specimen in only one case.

A possible explanation for the results indicating that the ultimate skidding resistance of a specimen made with rounded aggregate would be at least as good, and possibly better, than one made with a similar angular aggregate is related to the relative densities of the two mixtures. In the laboratory compaction and wearing procedure, the rounded aggregate, which permitted greater workability of the mixture, resulted in higher specimen densities than was the case for the angular aggregate. This was apparent in comparing the relative heights of specimens made with equal weights of rounded and angular aggregates. This resulted in a denser texture for the rounded aggregate than for the angular aggregate, with a correspondingly greater area of contact; and, as indicated in the previous section on surface texture, resulted in better anti-skid characteristics.

The sandstone specimen made with rounded aggregate exhibited the same increase in skidding resistance, as wearing progressed, that was noted with the specimens tested in the surface texture study. As the surrounding matrix eroded away, the effect of the additional resistant sandstone increased the anti-skid resistance.

THE SKIDDING RESISTANCE OF SELECTED DENSE-TEXTURED MIXTURES

The investigation of the effect of test specimen surface texture on the skidding resistance of bituminous mixtures led to the conclusion that dense-textured surfaces possess higher anti-skid resistance than open-textured surfaces. Similarly, in the review of literature it was indicated that dense surfaces, containing hard angular aggregate particles, possessed the best anti-skid characteristics of all the surface types tested. In order to investigate this relationship more fully, and also in order to study various materials as potential blending ingredients for improving the anti-skid characteristics of a polish-susceptible aggregate, 14 different dense-textured specimens were made and tested.

This section includes a description of the materials and the tests, the relative resistance values for the 14 surfaces after varying degrees of wear, and a discussion of results.

Description of Materials and Tests

The composition of the various mixtures is shown in Table 9. Nine of the specimens conformed to Gradation No. 5, which was the most dense-graded mixture of those used in the surface texture investigation. In addition to the four aggregate types (oolitic and dolomitic limestone, rhyolite, and sandstone) evaluated in the surface-texture investigation, two slags and three natural sands were included in this study of dense-textured mixtures.

SL-1 was a typical gray blast-furnace slag with a high degree of porosity. A photomicrograph of this material, which has been discussed previously, is included in Figure 16. SL-2 was a black, glassy non-porous slag, the product of a wet-bottom, coal-burning boiler.

The particle shapes of the three graded sands are shown in the left column of Figure 24. These enlarged photographs were made of material passing the No. 30 and retained on the No. 50 sieve. The Elkhart sand, appearing at the top of the column, is the most rounded of the three; the Lafayette sand is somewhat more angular than the Elkhart sand; and the Virginia sand is harsher than the Lafayette sand.

The other three materials shown in Figure 24 also were used in making dense-textured specimens. The very harsh silica sand, illustrated by the top figure in the right-hand column, was obtained from Virginia. The silica-sand

TABLE 9

Mixture Composition of Dense-Textured Specimens

Passing Sieve	Retained Sieve	Gradation No. 5	Silica Sand	Carbor- undum	Kentucky Rock Asphalt
No. 4	No. 8	19.2	0	0	0
No. 8	No. 16	15.1	0	0	1.7
No. 16	No. 30	14.0	0.5	88.1	4.3
No. 30	No. 50	13.3	38.4	11.7	43.3
No. 50	No. 100	15.1	56.7	0.1	37.2
No. 100	No. 200	13.7	4.0	0.1	6.8
No. 200	Pan	9.6	0.4	0	6.7
		100.0	100.0	100.0	100.0

Gradation No. 5 Specimens:

L-4, L-11, and SL-1 ----- 5.7 percent asphalt

All other aggregates ----- 5.4 percent asphalt

Silica Sand Specimen:

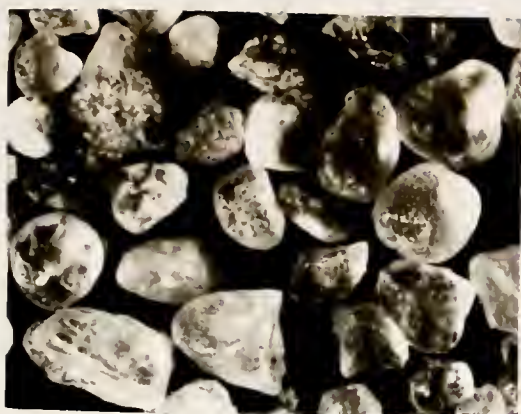
1700 g. of silica sand; 40 g. hydrated lime; and
6.2 percent asphalt.

Carborundum Specimen:

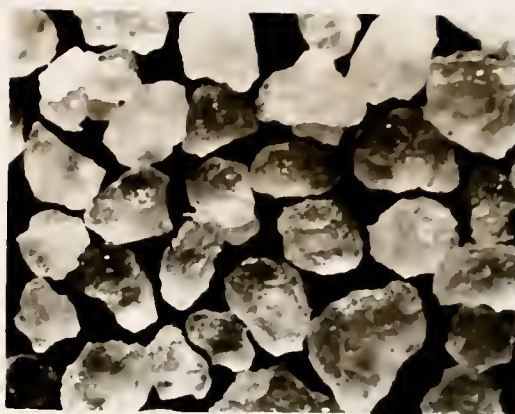
900 g. of silica sand; 900 g. carborundum;
40 g. hydrated lime; and 5.7 percent asphalt.

Kentucky Rock Asphalt Specimen:

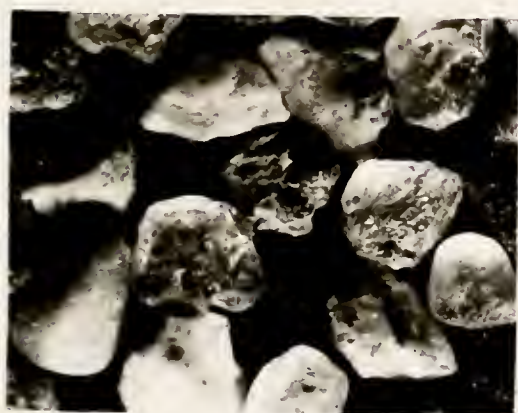
1800 g. of the total natural material, of which
8.03 percent was asphalt, as determined by extraction.



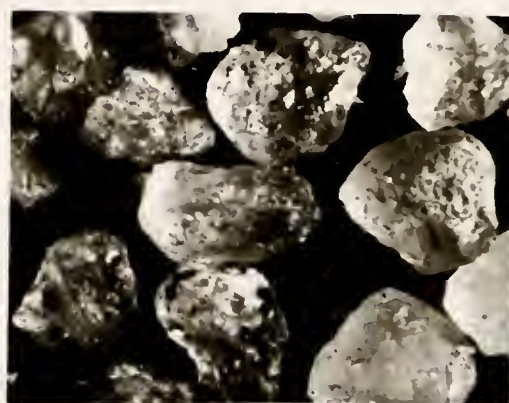
ELKHART SAND



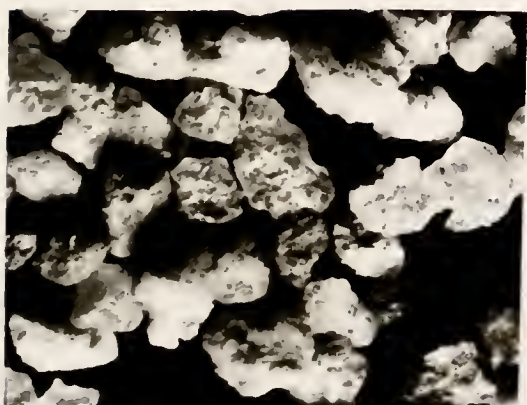
SILICA SAND



LAFAYETTE SAND



KENTUCKY ROCK ASPHALT



VIRGINIA SAND



CARBORUNDUM

FIG. 24 PARTICLE SHAPE OF MATERIALS USED FOR DENSE-TEXTURED SPECIMENS

mixture listed in Table 9 is representative of a type of non-skid treatment which has been used very successfully in that State.

The enlarged photograph of particles contained in Kentucky rock asphalt was made after the asphalt had been extracted from the specimen. These hard quartz particles are somewhat less angular than the silica sand.

The remaining print in Figure 24 is of a sample of carborundum, and while it may not be practical to use this material as a highway aggregate, it was felt that the effect of a small amount of an artificial abrasive on the skidding characteristics of a bituminous mixture containing a polish-susceptible aggregate would be of some interest. The degree of harshness of carborundum is similar to that of silica sand. In selecting a suitable mixture for a dense-textured specimen, carborundum and silica sand were combined in equal parts by weight, as indicated in Table 9.

The other specimens included in the dense-textured category were a surface which consisted entirely of 85-100 penetration asphalt cement and a specimen of solid ice. The asphalt-cement specimen was tested in the wet condition only, and the ice in both the dry and wet conditions. These surfaces were included to indicate the relative resistance values for the most slippery conditions that might be encountered on a highway surface.

The fourteen specimens were tested in the laboratory skid-test apparatus in the conventional manner. However, only the nine specimens conforming to Gradation No. 5 were subjected to the standard wear and polishing procedure. The three dense non-skid mixes did not possess sufficient surface durability, and disintegrated due to the severe wearing action. The three test specimens of this nature, on which skidding results were obtained, were given only a slight amount of wear in the skid-test apparatus, using quartz as the abrasive material.

Discussion of Results

The relative resistance values for the dense-textured specimens are listed in Table 10. A comparison of the skidding resistance at the completion of the fine-polish cycle of the nine mixes, conforming to Gradation No. 5, with the other surface types is shown in Figure 25.

Results for mixtures containing the four aggregates, which had been included in the aggregate comparison study using the standard specimen, indicate about the same degree of effectiveness in developing anti-skid resistance, relative to each other, that was found in the previous study. Bituminous mixtures containing dolomitic limestone and rhyolite exhibited appreciably better skidding resistance than those made with oolitic limestone, while sandstone bituminous mixtures gave by far the best anti-skid characteristics.

TABLE 10

Summary of Results on the Skidding Resistance of
Selected Dense-Textured Specimens

A. Dense-Graded Bituminous Mixtures (Gradation No. 5):

Aggregate Identification	RRV after the following cycle:		
	Initial Rolling	Coarse Wear	Fine Polish
I-11 Oolitic Limestone	.60	.48	.42
L-4 Dolomitic Limestone	.80	.68	.65
R-1 Rhyolite	.80	.72	.60
S-2 Sandstone	.82	.86	.86
SL-1 Vesicular Slag	.82	.72	.66
SL-2 Non-Porous Slag	.77	.67	.54
Lafayette, Ind. Sand	.76	.75	.67
Elkhert, Ind. Sand	.70	.66	.64
Virginia Sand	.74	.74	.75

B. Dense Non-Skid Bituminous Specimens:

Description of Specimen	RRV after a limited amount of wear
Virginia Silica Sand	1.01
Silica Sand and Carborundum	1.02
Kentucky Rock Asphalt	.96

C. Dangerously Slippery Specimens:

Description of Specimen	RRV - No Wear
85-100 Penetration Asphalt - Wet	.12
Ice at minus 20 F.	.15
Wet Ice	.11

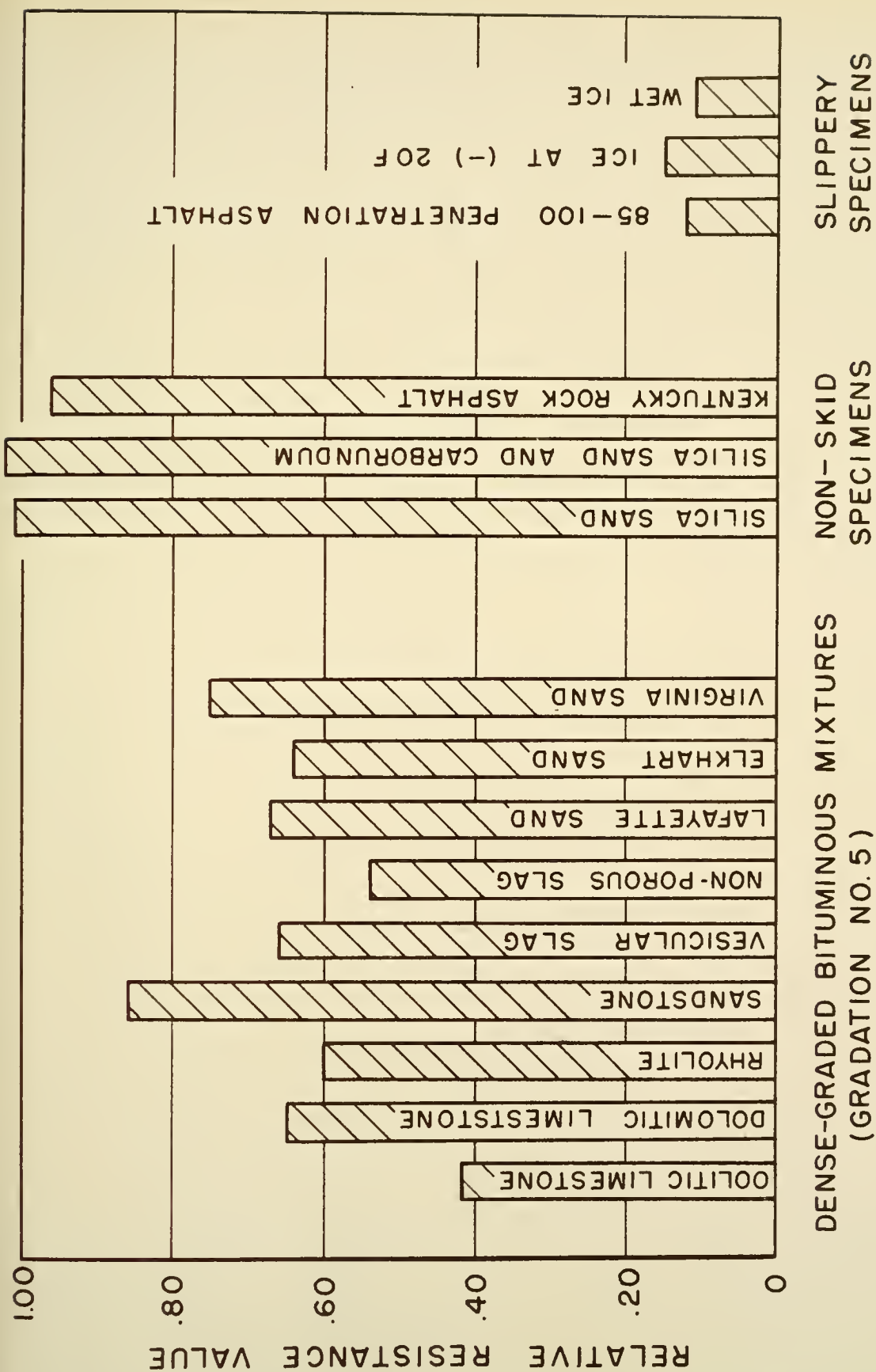


FIG. 25 THE SKIDDING RESISTANCE OF SELECTED
DENSE-TEXTURED SPECIMENS

The vesicular slag gave results which were comparable to those of the dolomitic limestone, and appreciably higher than for the non-porous slag.

The three graded natural sands all exhibited good anti-skid characteristics. Bituminous mixtures containing Elkhart, Lafayette, and Virginia sand gave relative resistance values of 0.64, 0.67, and 0.75, respectively. As indicated by Figure 24, and mentioned previously, the Elkhart sand was the most rounded and the Virginia sand the most angular of the three. Consequently, it would appear that the skidding resistance of the dense-textured bituminous mixtures is dependent to some degree on the angularity of the aggregate particles.

The three "non-skid" surface types all exhibited excellent anti-skid characteristics. The laboratory Kentucky rock asphalt specimen had an RRV of 0.96, which was slightly less than the value obtained on a Kentucky rock asphalt specimen cored from the pavement surface. This was probably due to the fact that the texture of the laboratory specimen was more uniform than that of the field specimen, in which some of the particles were dislodged from the surface, resulting in a slightly roughened texture.

The silica-sand and the combination silica-sand and carborundum specimens gave essentially equal results. They both exhibited somewhat better anti-skid resistance than the laboratory Kentucky rock asphalt specimen, probably due

to greater angularity of the individual particles.

The three remaining values plotted in Figure 25 are representative of surface types exhibiting the poorest characteristics, from the standpoint of skidding resistance, of any highway surface likely to be encountered. Wet ice had an RRV of 0.11, with a wet asphalt surface only slightly higher at 0.12. These values were included to provide a better appreciation of the significance of a low relative resistance value.

BLENDING OF SKID-RESISTANT MATERIALS
WITH A POLISH-SUSCEPTIBLE AGGREGATE

In many parts of the United States the primary aggregate used in highway pavement construction is limestone; and, as shown by the results on the skidding resistance of bituminous mixtures made from 22 different aggregates, limestones, as a group, do not produce mixtures that exhibit high anti-skid resistance. Some of the limestones polish excessively, becoming extremely slippery when wet; and the best limestone evaluated in this study had appreciably lower skidding resistance than the average value for the other ten aggregate types.

Since, from economic considerations, it is necessary to use limestone in many highways, the purpose of this phase of the research program was to investigate the effect of blending a resistant material with a polish-susceptible limestone in an effort to obtain good anti-skid resistance in the resulting bituminous mixture. From the practical standpoint most of the blending materials were in the fine aggregate range, but two coarse aggregate substitutions were also made in order to determine if this procedure was more effective than fine aggregate replacement in improving

the skidding characteristics of a polish-susceptible aggregate.

The limestone selected as the polish-susceptible aggregate was L-4, an oolitic limestone, available in quantity, and one which had exhibited very little resistance to polishing. The RRV at the completion of the fine-polish cycle for bituminous mixtures containing this aggregate was 0.34. This aggregate was used as the basic limestone in all of the blending study specimens.

Included in this section is a description of the blending materials and the skidding resistance results for coarse aggregate substitution, for fine aggregate substitution, and for fine aggregate combination. Also, included is a comparison of the effectiveness of the three different treatments.

Coarse Aggregate Substitution

The two coarse aggregates which were used in this study as replacements materials were SL-1, a vesicular slag, and S-2, a calcareous sandstone. The gradation and the asphalt contents of all mixtures for this phase of the study conformed to the standard laboratory specimen, previously defined.

The fraction of the material on which the substitution was made was that passing the 1/2-inch sieve and retained on the No. 4 sieve. This constituted 46 percent of the

total aggregate. The amount of replacement material for each of the five mixes was as follows:

Mixture Identification:	1	2	3	4	5
Percent Substitution Based on Coarse Aggregate:	0	25	50	75	100
Percent Substitution Based on Total Aggregate:	0	12	24	36	48

Since 48 percent of the total mix was coarse aggregate, 100 percent replacement of the coarse aggregate corresponded to 48 percent of the total aggregate.

These specimens were subjected to the conventional testing and polishing procedure, and the results are shown graphically in Figure 26. The five curves drawn for each type of replacement material represent the results for a bituminous mixture in which the aggregate consisted entirely of oolitic limestone, and for mixtures containing, respectively, 25, 50, 75, and 100 percent coarse aggregate replacement.

For the initial testing cycle replacing a part of the coarse aggregate fraction resulted in a slight improvement in skidding resistance, with the degree of effectiveness increasing with the percent of substitution. This advantage became more significant as wear and polish progressed. The sandstone was much more effective in improving the anti-skid characteristics of the mixtures than the slag. A complete sandstone coarse aggregate replacement increased the RRV of a pure limestone specimen at the end of the

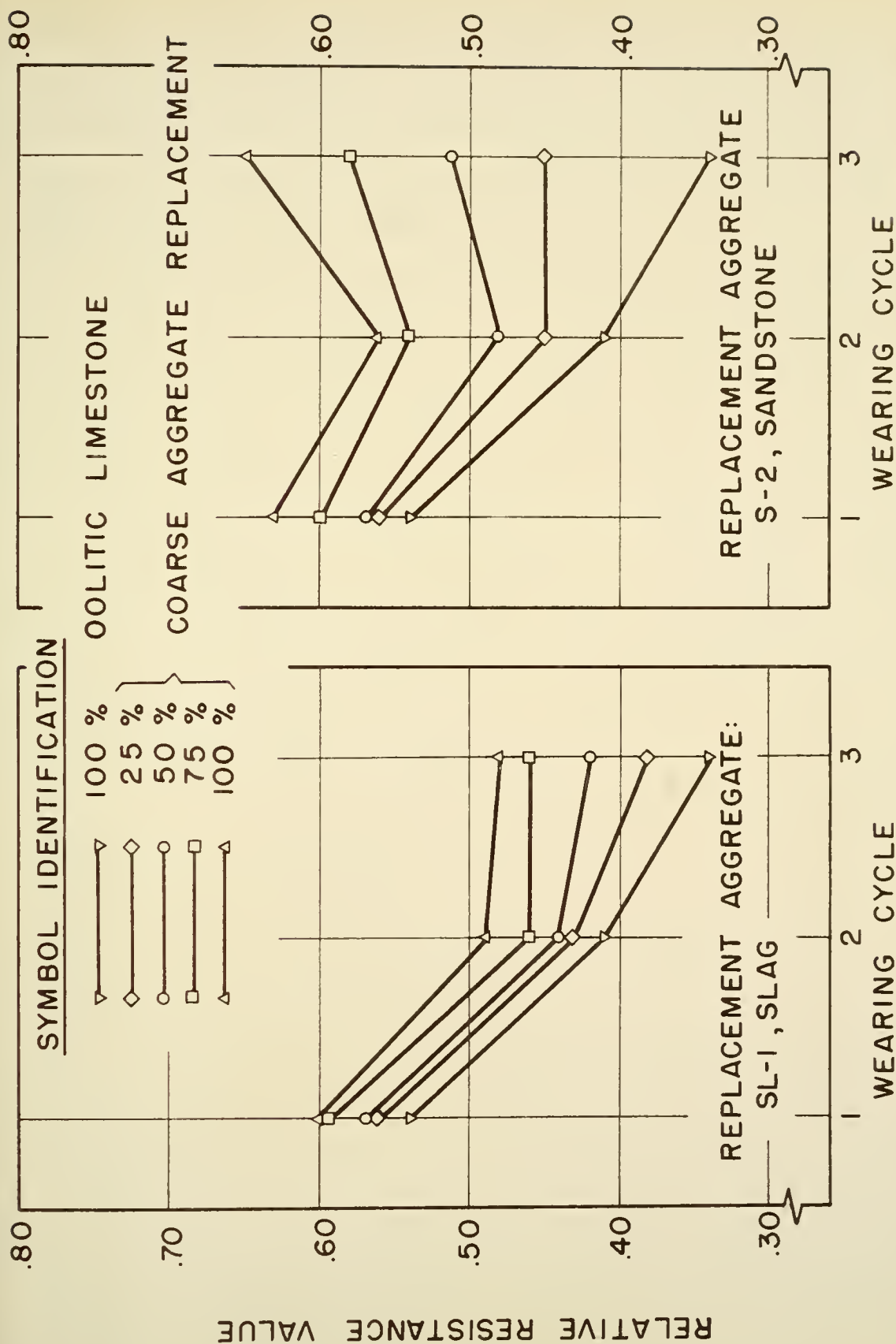


FIG. 26 EFFECT OF REPLACING THE COARSE AGGREGATE FRACTION WITH A POLISH RESISTANT MATERIAL

fine-polish cycle from 0.34 to 0.65; a similar slag replacement increased the RRV to 0.49. A 50 percent substitution of the coarse aggregate with sandstone, resulting in an RRV of 0.51, was more effective than a 100 percent coarse aggregate replacement with slag.

An interesting aspect of the sandstone replacement specimens was the fact that their anti-skid resistance actually improved during the slow-wear and fine-polish cycles. Although there was an appreciable decrease in the skidding resistance of the specimens during the coarse-wear procedure, in which the angularity of the aggregate was reduced, subsequent polishing served to wear and erode away the softer limestone and asphalt matrix, and provided greater exposure of the skid-resistant sandstone. The specimen, in which the limestone coarse aggregate was entirely replaced by sandstone, exhibited better anti-skid resistance at the completion of the fine-polish cycle than it had shown initially.

Fine Aggregate Substitution

The specimens for evaluating fine-aggregate substitution also conformed to the standard laboratory specimen in gradation and asphalt content. The fraction of the material replaced was that passing the No. 4 sieve and retained on the No. 100 sieve. Forty-seven percent of the total aggregate fell within this range. The amount of replacement

material for each of the five mixes was as follows:

Mixture Identification:	1	2	3	4	5
Percent Substitution Based on Fine Aggregate:	0	25	50	75	100
Percent Substitution Based on Total Aggregate:	0	11.8	23.5	35.3	47.0

Four fine aggregate replacement materials were investigated. In addition to the vesicular slag and calcareous sandstone, used in the coarse aggregate substitution study, a glassy non-porous slag (SL-2) and a natural sand from Lafayette, Indiana, also were included.

The test specimens were subjected to the conventional testing and polishing procedure, and the results are shown graphically in Figures 27(a) and 27(b). As with the coarse aggregate substitution, the lowest curve of the five represents the results for a bituminous mixture made entirely with oolitic limestone with the other four curves representing mixtures which contain, respectively, 25, 50, 75, and 100 percent fine aggregate replacement.

In comparing the effectiveness of the four different replacement materials at the beginning of the wearing cycle, it is noted that both of the slags provided an appreciable improvement in the skidding resistance, that was greater for increasing amounts of substitution; the sandstone was somewhat less effective; and the Lafayette sand caused no significant change from the RRV determined for the 100 percent limestone specimen. The Lafayette

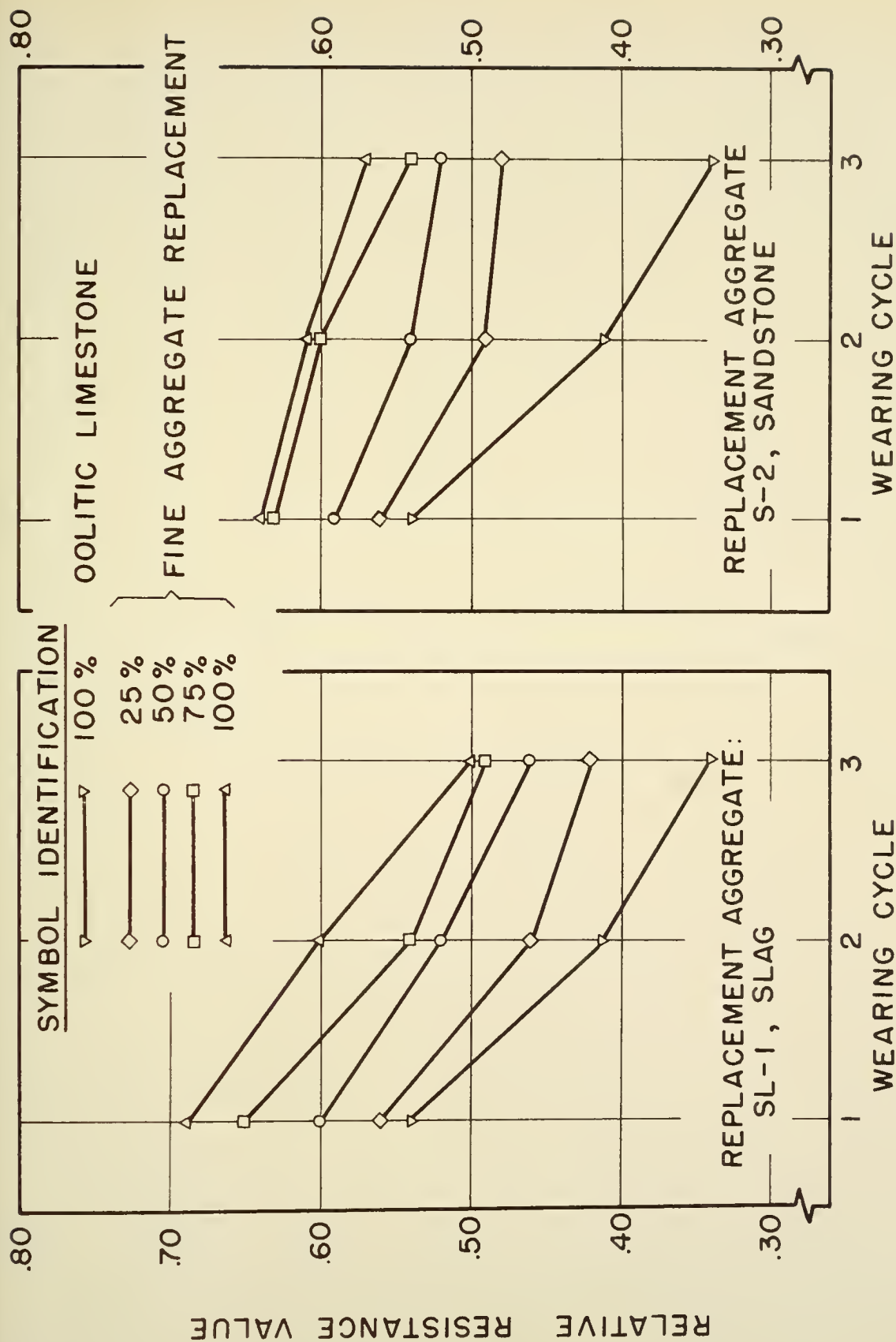


FIG. 27a EFFECT OF REPLACING THE FINE AGGREGATE FRACTION WITH A HARDER MATERIAL

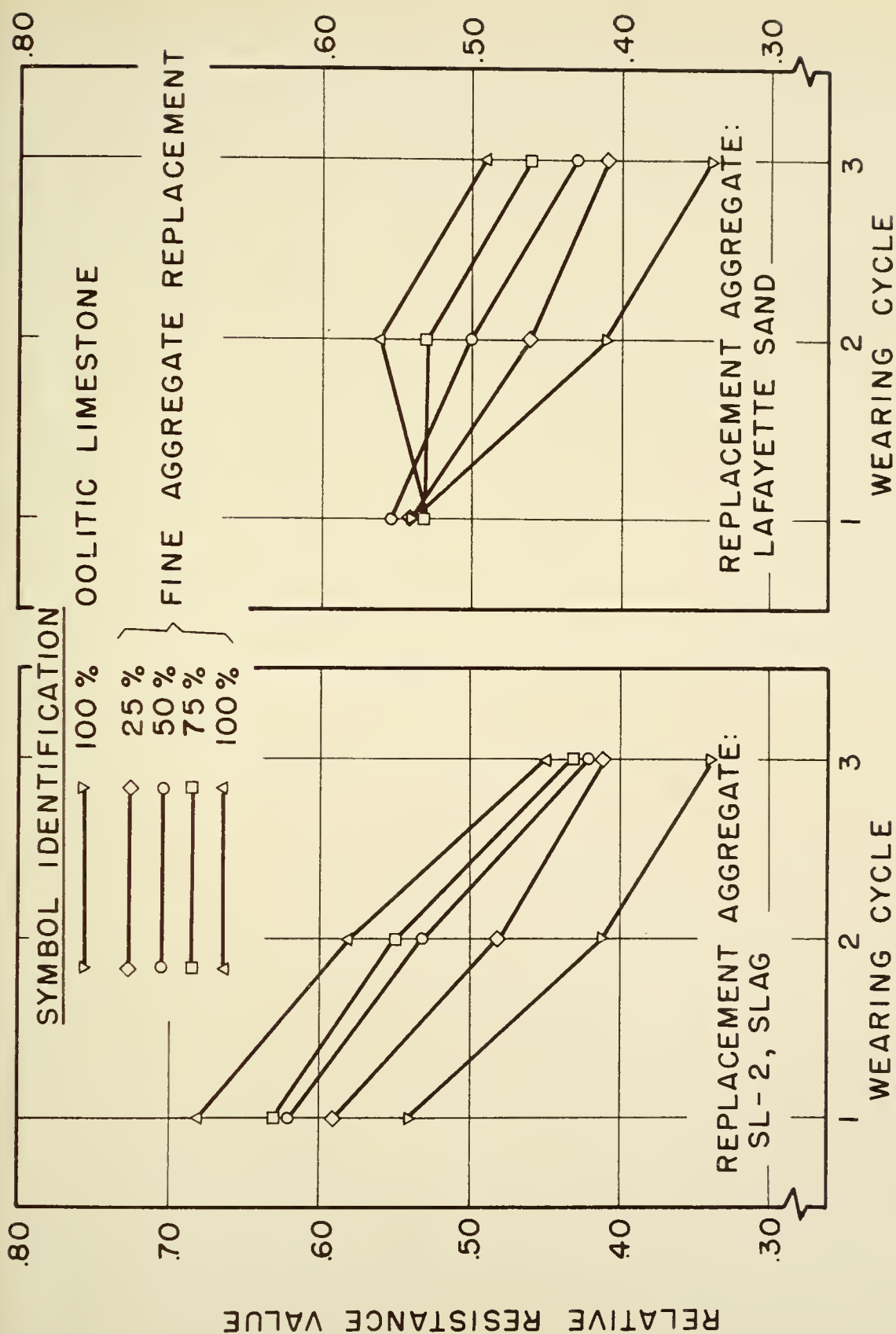


FIG. 27b EFFECT OF REPLACING THE FINE AGGREGATE FRACTION WITH A HARDER MATERIAL

sand was more rounded than the crushed limestone that it replaced, so even though it was an appreciably harder material, the two effects compensated in the initial condition, and the skidding resistance was unaffected by the substitution.

After an appreciable amount of wear, as indicated by the results at the completion of the fine-polish cycle, the relative effectiveness of the four materials was different from that of the initial condition. The sandstone was the most effective, in that it resulted in an increase in the RRV from 0.34 to 0.57 for a 100 percent fine aggregate replacement; the vesicular slag and Lafayette sand resulted in RRV's of 0.50 and 0.49, respectively, for 100 percent fine aggregate replacement; and the non-porous slag was the least effective of the four materials, with a total fine aggregate substitution giving an RRV of only 0.45.

Fine Aggregate Combination

The two materials used in this phase of the investigation were not sufficiently well-graded to be included as replacement material. As indicated in Table 9, the majority of the silica sand passed the No. 30 sieve and was retained on the No. 100 sieve. A complete replacement of this fraction would result in a substitution of only 14 percent of the total aggregate. Similarly, the carborundum fell essentially within the No. 16 to No. 30 range.

Consequently, instead of replacing a certain fraction of the oolitic limestone, as in the two related phases of this study, the material was combined with a quantity of limestone, which conformed to the standard gradation. This resulted in a surface texture somewhat more dense than that of the standard specimen, with the texture becoming increasingly dense as the percentage of fine combination material was raised.

For the silica sand specimens, sufficient material, conforming to the gradation of Table 9, was combined with the standard limestone mix to result in specimens with 10, 20, 30, and 40 percent, respectively, of silica sand, based on the total weight of the aggregate. Smaller amounts of carborundum were used, with the mixes containing 5, 10, 15, and 20 percent, respectively, also based on the total aggregate weight.

These specimens were subjected to the standard testing and wearing procedure, and the results are shown graphically in Figure 28. The combination of these non-skid materials with the oolitic limestone resulted in a significant increase in the anti-skid properties of the mixture for all degrees of wear. There was probably a slight increase in skidding resistance of the mixtures due to the denser surface texture, but most of the improvement was attributable to the nature of the harsh, polish-resistant particles which were added.

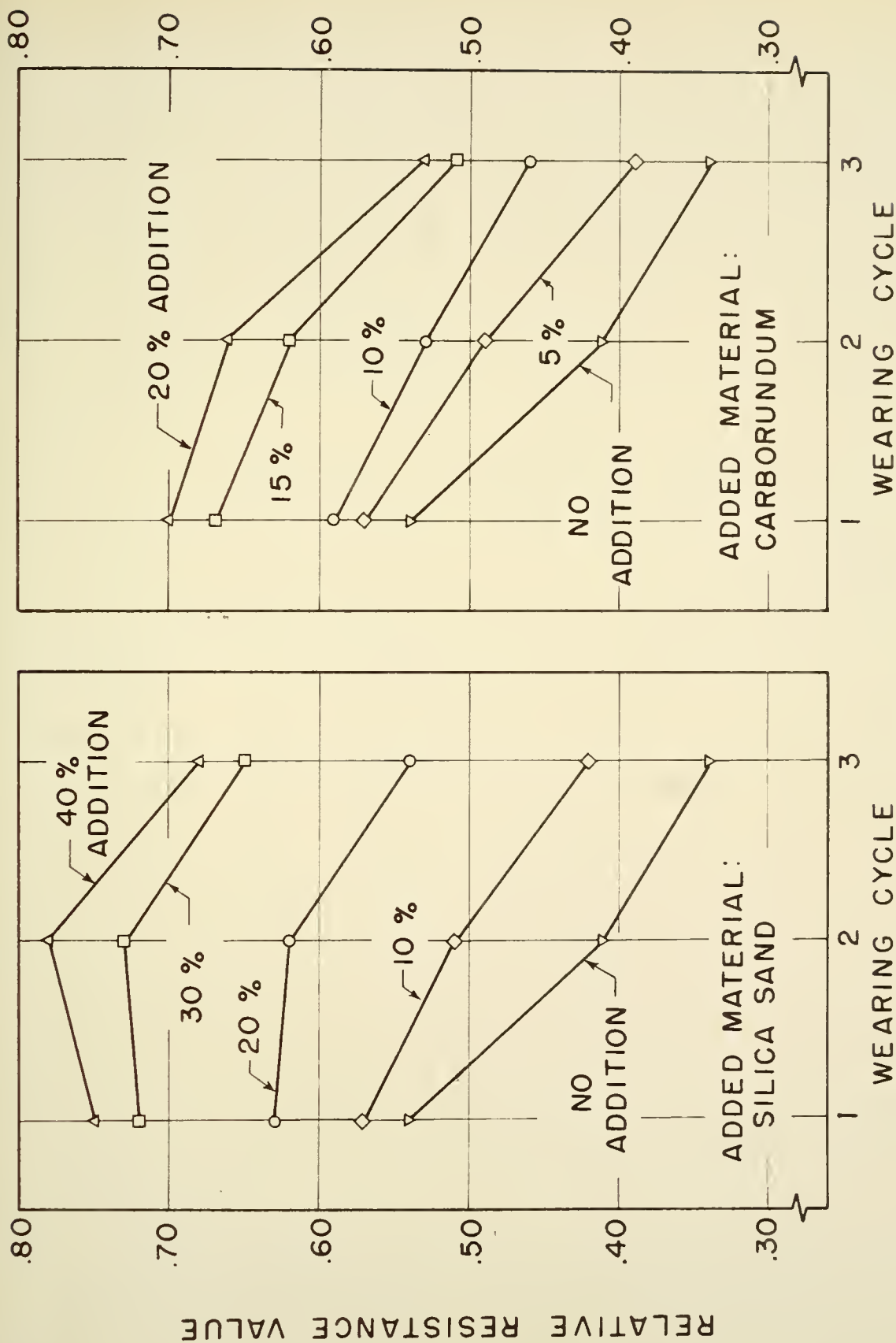


FIG. 28 EFFECT OF COMBINING A NON-SKID MATERIAL WITH A POLISH-SUSCEPTIBLE AGGREGATE

A 20 percent addition of silica sand increased the RRV of an oolitic limestone specimen at the completion of the fine-polish cycle from 0.34 to 0.54, while a 40 percent addition doubled the RRV to 0.68. The addition of carborundum gave slightly higher anti-skid properties to the mixtures than did an equal percentage of silica sand in the early phases of the wearing procedure, but at the completion of the fine-polish cycle the difference was negligible.

Effectiveness of the Blending Treatments

A graphical comparison of the relative effectiveness of the various blending treatments is presented in Figure 29. This figure shows the relative resistance values at the completion of the fine-polish cycle, both for a specimen in which the aggregate consisted entirely of oolitic limestone and for specimens representing each of the blending treatments. Mixes selected for comparison contained the blending ingredient in a proportion of approximately one part to two parts of oolitic limestone. The coarse- and fine-aggregate substitution specimens had a higher amount of blending material, i.e., 36 and 35.3 percent, than the fine-aggregate combination specimens, which contained 30 percent silica sand and 20 percent carborundum, respectively.

Even though the percentage of blending material was slightly less than for the coarse and fine-aggregate

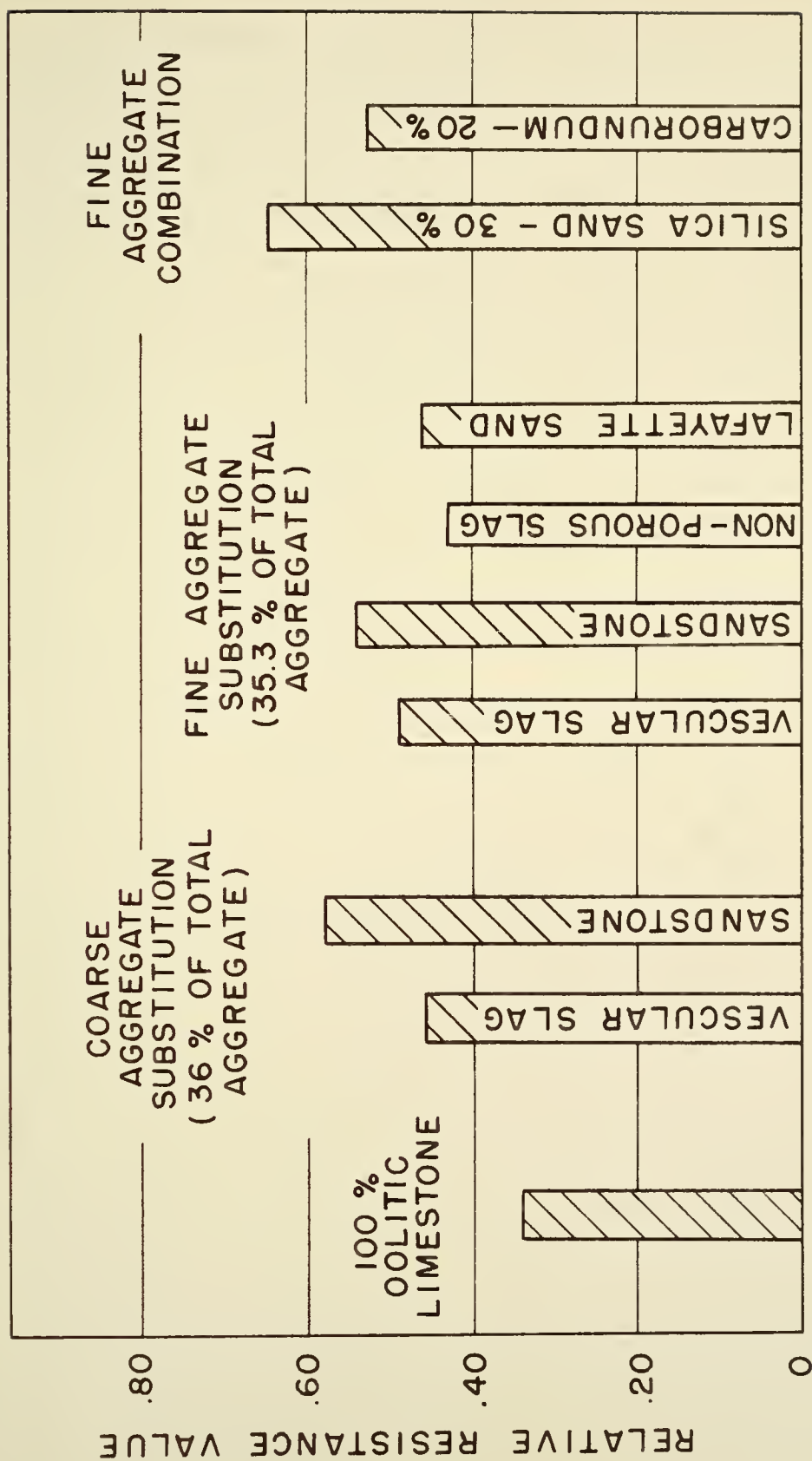


FIG.29 THE EFFECT OF BLENDING VARIOUS MATERIALS WITH A POLISH-SUSCEPTIBLE OOLITIC LIMESTONE

replacement treatments, combining silica sand with the oolitic limestone was the most effective method of improving the anti-skid characteristics of the test specimens. As previously indicated, the improved skidding resistance may have been due in part to the denser texture, resulting from the addition of a fine material to the standard gradation, but was probably primarily dependent upon the harsh abrasive nature of the silica sand. In addition to the high resistance presented by the individual silica-sand particles, there also is evidence to indicate that the presence of the sand prevented the large limestone particles from becoming so highly polished. One series of laboratory tests proved that grinding on a limestone test specimen with coarse silica sand, after it had been polished to its most slippery condition using limestone mineral filler as the abrasive, resulted in an increase in RRV of 0.17.

The addition of carborundum had essentially the same effect as an equal amount of silica sand. Since it is a great deal more expensive than silica sand, the use of this material for the purpose of improving the skidding resistance of bituminous mixtures is not discussed further.

The next most effective material was S-2, the calcareous sandstone. As illustrated in Figure 29, in both the coarse- and fine-aggregate replacement specimens, the mixtures containing sandstone exhibited the highest anti-skid resistance of all specimens included in the respective type

of treatment. The vesicular slag showed somewhat better blending characteristics than the Lafayette sand, while the glassy, non-porous slag had the least effect of any of the materials in improving the skidding resistance. A 75 percent fine-aggregate replacement of SL-2 caused an increase in RRV of from 0.34 to only 0.43. Although the individual slag particles were hard and had sharp corners, they also possessed flat glassy faces which, under the kneading action of the rolling procedure, were oriented parallel to the surface and developed very little skidding resistance during testing.

On the basis of the limited data presented by this study, there appears to be little difference between the relative effectiveness of coarse- and fine-aggregate replacement. For the two aggregates on which such a comparison was possible, i.e., S-2 and SL-1, there was disagreement. For the sandstone specimens, a 75 percent coarse-aggregate replacement resulted in an RRV of 0.58, and a 75 percent fine-aggregate replacement a value of 0.54. For the slag, however, the fine-aggregate replacement resulted in a higher RRV (0.49) than did the coarse-aggregate replacement (0.46).

A possible explanation for the advantage of the coarse sandstone replacement over the fine lies in the petrographic description of the material. This aggregate consisted of coarse quartz particles, averaging about 0.3 mm in diameter,

bound in a matrix of calcite. During the crushing and sieving operation the individual quartz particles were not reduced in size, but the weaker cementing grains did break down very readily to finer material. Consequently, very little of the minus No. 16, and practically none of the minus No. 30 material, was quartz. As a result, the coarse-aggregate replacement, which was based on the material retained on the No. 4 sieve, was somewhat higher in quartz content than the fine-aggregate replacement, which included the smaller sieve fractions. It was the harsh, resistant quartz particles in the sandstone, rather than the weak calcite grains, which brought about an improvement in skidding characteristics of the mixtures, so the coarse sandstone was a more effective replacement material than the fine sandstone.

SUMMARY OF RESULTS

The following summary is a brief recapitulation of the major findings of the laboratory testing program leading to this dissertation. The standard specimen, on which the majority of the test data was based, was a fairly open-graded asphaltic concrete with the asphalt content kept intentionally low to emphasize the effect of the aggregate on the anti-skid characteristics of the mixture. Each test specimen, except those involved in the blending investigation, was composed entirely of one type of aggregate, since a comparison of the effect of different types of aggregates on the skidding characteristics of bituminous mixtures could best be accomplished by this means. All results pertain to the surfaces in the wet condition.

1. The type of bituminous paving mixture which exhibited the best anti-skid resistance was a dense-textured* surface consisting of hard, angular quartz particles, as typified by a silica-sand or a Kentucky rock asphalt surface.

2. On the basis of the 22 aggregates evaluated in this study, the aggregate type which imparted by far the best anti-skid characteristics to the standard bituminous concrete test specimen was sandstone.

* Refer to "TERMINOLOGY", page xii.

3. Limestones, as a group, exhibited poor anti-skid characteristics when used as the total aggregate in bituminous mixtures. At the completion of the fine-polish cycle, the average relative resistance value for specimens made with the twelve different limestones was 0.45, and for the ten other aggregates 0.63. On the basis of the field correlation study, it would appear that a coefficient of friction of 0.40, which is the recommended minimum permissible value for wet pavement surfaces in several states, is approximately equivalent to a relative resistance value of 0.60. The average RRV of 0.45 for the limestone bituminous mixtures was appreciably below this recommended minimum.

4. There was a great deal of variability in the resistance to polishing of the different varieties of limestone. Bituminous mixtures composed of limestone which was essentially pure calcium carbonate exhibited the poorest anti-skid characteristics, with relative resistance values falling in the low-to-middle 0.30's. Specimens consisting of limestone high in "impurities", which for this study was primarily magnesium carbonate, exhibited better anti-skid resistance than mixtures made with high-calcium limestone. RRV's for specimens containing highly-dolomitic limestones were all in the 0.50's at the end of the fine-polish cycle, with a high value of 0.56 being recorded for one series of test specimens.

5. Dense-textured test specimens exhibited better anti-skid resistance than open-textured specimens composed of the same aggregate during all phases of the wear and polish procedure.

6. Test specimens made from freshly-crushed aggregate possessed greater skidding resistance in the early stages of the laboratory wearing procedure than did specimens composed of the same aggregate which had been rounded in the Los Angeles abrasion machine prior to batching. At the completion of the fine-polish cycle, however, the rounded-aggregate specimens exhibited anti-skid resistances equal to those of specimens made with freshly-crushed aggregate.

7. For dense mixtures consisting of material passing the No. 4 sieve, and composed of appreciable quantities of hard aggregate such as quartz, the angularity, or degree of harshness, of the individual particles had some effect on the skidding resistance of the mixture. The greater the angularity, the better the anti-skid resistance.

8. It was possible to improve the skidding resistance of a bituminous mixture made with a polish-susceptible oolitic limestone by blending any of a variety of polish-resistant materials with the limestone. However, not all materials were equally effective in improving the anti-skid characteristics of the mixtures, and in order to accomplish a significant increase in RRV at the end of the fine-polish

cycle it was necessary to add an appreciable amount of even the most effective blending ingredient.

9. The two most effective natural blending materials evaluated in this study were silica sand and calcareous sandstone. A 25 percent addition of silica sand, based on the total weight of the aggregate, or a 40 percent replacement with sandstone, effected an increase in RRV at the end of the fine-polish cycle of from 0.34, for a specimen composed entirely of oolitic limestone, to approximately 0.60.

10. The addition of the only natural graded sand included in this study, i.e., the Lafayette sand, had little effect on improving the anti-skid characteristics of a bituminous mixture made with a polish-susceptible limestone. There was no increase in RRV for the initial test series; and, after the entire wear and polish procedure, a 48 percent replacement of the total aggregate with Lafayette sand resulted in an increase in RRV of from 0.34 to 0.48. Smaller percentages of replacement had a lesser effect.

CONCLUSIONS

The following conclusions are intended to reflect the major findings of this program of research. Since this was a laboratory study, restricted in scope with regard to materials and methods, the limit to which this knowledge can be extended to predict the behavior of bituminous pavements may be subject to debate. The nature of these conclusions is probably not completely objective and may reflect, to a slight degree, the opinions and the experience that the author has acquired during a nine-year period of interest in factors pertaining to pavement slipperiness. With these limitations in mind the following conclusions, which apply to surfaces in the wet condition only, are presented:

1. It is possible, in a laboratory investigation, to evaluate many of the important variables contributing to pavement slipperiness, and to arrive at a more accurate determination of some of these individual variables than can be obtained in a field testing program. On the basis of the field correlation study, and after eleven months of reasonably continuous use, it would appear that the laboratory equipment and procedure for evaluating skidding characteristics of bituminous paving mixtures has been entirely

satisfactory. A comparison of the methods and results of this testing program with those of many reputable field and laboratory investigations, both in this country and in Europe, tends to substantiate this statement.

2. It is impossible, on the basis of the three standard physical tests of the aggregate included in this study, to predict the skidding characteristics of a bituminous mixture composed of that aggregate. There was no correlation between the resistance of an aggregate to polishing and its specific gravity, percent absorption, or loss on abrasion.

3. A petrographic and a chemical analysis of an aggregate may help to indicate the anti-skid resistance of bituminous mixtures made from the aggregate. The size, angularity, degree of interlock, and difference in hardness of the individual grains, which show up in a thin-section, are related to the polishing characteristics of the aggregate. Similarly, for the twelve limestones evaluated in this study there was a high correlation between the tendency of an aggregate to polish and the calcium carbonate content.

4. Limestones that are essentially pure calcium carbonate should not compose the entire wearing surfaces of bituminous pavements, even if the anticipated traffic is relatively low. Surfaces of this nature possess poor anti-skid resistance when new, and become dangerously slippery after a moderate amount of traffic.

5. Bituminous surfaces composed entirely of highly-dolomitic limestone may be expected to exhibit adequate anti-skid characteristics for a reasonable period of time if severe traffic is not anticipated. These surfaces can ultimately polish; and, if traffic is excessive, may do so in a relatively short period. However, this same observation also can be made for surfaces containing some of the so-called resistant aggregates, such as rhyolite, chert, and high-quartz gravel.

6. In order for a pavement constructed with conventional highway materials to retain a permanent non-skid surface, some type of coarse particle-by-particle wear, such as occurs with a silica-sand or a Kentucky rock asphalt surface, is necessary. On surfaces of this nature the individual quartz particles are resistant to wear, and are dislodged from the surface before they have the opportunity to polish excessively. This action continually rejuvenates the surface. This same condition exists to a lesser degree with bituminous mixtures composed of sandstone, which showed the best resistance to polishing of any of the aggregates evaluated in this study. In a calcareous sandstone the resistant quartz particles are ejected from the surrounding calcite matrix before they polish appreciably.

7. Dense-textured* bituminous pavements exhibit better anti-skid resistance than open-textured surfaces constructed

* Refer to "TERMINOLOGY", page xii.

of the same materials, provided an excess of asphalt is not present at the surface.

8. There is some justification, based on anti-skid considerations alone, for requiring that the aggregate appearing in the surfaces of bituminous pavements be crushed. Initially, bituminous pavements containing crushed aggregate possess greater skidding resistance than pavements made from similar rounded aggregate. After an appreciable period of wear, however, the skidding resistances of the two surfaces will be nearly identical.

9. It is possible to improve the anti-skid characteristics of a bituminous mixture composed of a polish-susceptible aggregate by blending in a polish-resistant material. However, in order to effect a significant improvement, an appreciable substitution of a harsh, abrasive material, such as silica sand or sandstone, is required.

SUGGESTIONS FOR FUTURE RESEARCH

Recognizing that the program of research leading to this thesis was but an introductory work in the study of pavement slipperiness, the following recommendations for future research, which are intended to be both pertinent and practical, are listed:

1. An effort should be made to correlate the laboratory wear and polish procedure with a given amount and type of traffic. The standard procedure was developed to cause a bituminous mixture containing a polish-susceptible aggregate to approach its most slippery condition, and has no direct relationship to a definite amount of traffic wear.

2. Density and stability measurements should be performed on laboratory specimens which have been subjected both to the standard molding and to the standard wear and polish procedures, to see that the resulting specimens are representative of similar mixes existing as actual highway surfaces. The standard procedure was developed to simulate only the surface texture of comparable highway specimens.

3. The program of research leading to this dissertation was primarily an aggregate investigation; and, to emphasize the effect of the aggregate, the asphalt content was kept intentionally low. An investigation of the

skidding characteristics of bituminous mixtures at the optimum asphalt content, as determined by an accepted design procedure, would be of interest. Related research would include a study of the effect of asphalt content, of the type of bituminous binder, and of the type of mixture, i.e., whether an asphaltic concrete, surface treatment, etc., on the skidding characteristics of a test specimen.

4. The variety of aggregate types was not exhausted in this initial study. By evaluating the anti-skid characteristics of bituminous mixtures containing other aggregate types, and comparing these results with the petrographic and chemical analyses of the aggregates, the original findings as to the effect of the basic aggregate properties on their polishing characteristics could be extended.

5. Only a limited amount of data was obtained for natural sands and gravels, which actually constitute an appreciable percentage of the highway construction material. An extensive investigation of the composition of different sands and gravels, along with the anti-skid characteristics of bituminous mixtures composed of these aggregates, would contribute to a better understanding of these materials.

6. A related program of study with portland cement concrete test specimens would broaden the scope of this research appreciably.

BIBLIOGRAPHY

1. "Accident Facts - 1957 Edition," Bulletin of Statistics Division, National Safety Council, 1957.
2. Agg, T. R., "Tractive Resistance and Related Characteristics on Roadway Surfaces," Bulletin No. 67, Iowa Engineering Experiment Station, 1924.
3. Bird, G. and Scott, W. J. O., "Road Surface Resistance to Skidding," Road Research Technical Paper No. 1, Department of Scientific and Industrial Research, London, England, 1936 (H. M. Stationery Office).
4. Bressot, Chairman's Report, Committee on Slipperiness, Presented at the 10th Congress in Istanbul, Permanent International Association of Road Congresses, Rue Paul-Cezanne, Paris 8, France, 1955.
5. Creamer, W. M. and Brown, R. F., "Application of a New Non-Skid Surface Treatment on Connecticut State Highways," Bulletin No. 184, Highway Research Board, 1957.
6. Dillard, J. H. and Alwood, R. L., "Providing Skid-Resistant Roads in Virginia," Proceedings, The Association of Asphalt Paving Technologists, Vol. 26, pp. 1-22, 1957.
7. Fleming, E. M., "Coefficients of Friction Between Rubber Tires and Concrete Road Surfaces," Proceedings, Highway Research Board, Vol. 14, pp. 214-216, 1934.
8. Giles, C. G. and Lee, A. R., "Non-Skid Roads," Proceedings, The Public Health and Municipal Engineering Congress, London, England, 1948.
9. Giles, C. G. and Lander, F. T. W., "The Skid-Resisting Properties of Wet Surfaces at High Speeds," Journal, Royal Aeronautical Society, London, England, pp. 83-94, February, 1956.
10. Giles, C. G., "The Skidding Resistance of Roads and the Requirements of Modern Traffic," Proceedings, Institute of Civil Engineers, London, England, Vol. 6, pp. 216-249, 1957.
11. Goodwin, W. A. and Whitehurst, E. A., "A Device for the Determination of Relative Potential Slipperiness of Pavement Mixtures," Paper presented at the 37th Annual Meeting of the Highway Research Board, 1958.

12. Gray, B. E., "Best Practice in the Achievement of Non-Skid Asphalt Surfaces," Proceedings, Highway Research Board, Vol. 14, pp. 199-216, 1934.
13. Grime, G. and Giles, C. G., "The Skid-Resisting Properties of Roads and Tyres," Proceedings of the Automobile Division, The Institute of Mechanical Engineers, London, England, 1954-55.
14. Grunau, D. L., and Michael, H. L., "Skid Characteristics of Pavement Surfaces in Indiana," Bulletin No. 139, Highway Research Board, 1956.
15. Hanson, E. H., "Laboratory Apparatus for Friction Tests Between Tires and Pavements," Proceedings, Highway Research Board, Vol. 17, pp. 136-143, 1937.
16. Klein, K. M. and Brown, W. J., "Skid-Resistant Characteristics of Oregon Pavement Surfaces," Bulletin No. 39-5, Oregon State Highway Department, 1936.
17. Lee, A. P., "Full-Scale Experiments in Road Research, With Special Reference to Surface Dressings and Thin Carpets," Road Paper No. 31, The Institution of Civil Engineers, London, England, 1950.
18. Martin, G. E., "Skid Resistance of Tar Road Surfaces," Proceedings, Highway Research Board, Vol. 14, pp. 217-224, 1934.
19. Martin, G. E., "Apparatus for Determining Skid Resistance of Pavements," Proceedings, Highway Research Board, Vol. 17, pp. 121-135, 1937.
20. McKesson, J. L., "Slippery Pavements--Causes and Treatments," Proceedings, The Association of Asphalt Paving Technologists, Vol. 18, pp. 1-18, 1949.
21. Moyer, R. A., "Skidding Characteristics of Road Surfaces," Proceedings, Highway Research Board, Vol. 13, pp. 123-168, 1933.
22. Moyer, R. A., "Skidding Characteristics of Automobile Tires on Roadway Surfaces and Their Relation to Highway Safety," Bulletin No. 120, Iowa Engineering Experiment Station, Ames, Iowa, 1934.
23. Moyer, R. A., "Further Skidding Tests with Particular Reference to Curves," Proceedings, Highway Research Board, Vol. 14, pp. 123-130, 1934.

24. Moyer, R. A., "Motor Vehicle Operating Costs, Road Roughness, and Slipperiness of Various Bituminous and Portland Cement Concrete Surfaces," Proceedings, Highway Research Board, Vol. 22, pp. 13-52, 1942.
25. Moyer, R. A. and Shupe, J. W., "Roughness and Skid Resistance Measurements of Pavements in California," Bulletin No. 37, Highway Research Board, 1951.
26. Moyer, R. A., "Recent Developments in the Measurements of Road Roughness and Skid Resistance," Proceedings, The Association of Asphalt Paving Technologists, Vol. 20, pp. 42-96, 1951.
27. Moyer, R. A., Ahlborn, G. and Nauta, J., "Summary of 1953 Skid Resistance Test Results on Typical California Road Surfaces," Special Report, Institute of Transportation and Traffic Engineering, University of California, Berkeley, 1953.
28. Nagin, H. S., Nock, T. G., and Wittenwyler, C. V., "The Development of Resinous Skid-Resistant Surfaces for Highways," Bulletin, No. 184, Highway Research Board, 1957.
29. Nagin, H. S. and others, "The Development of Techniques for Applying Resinous Skid Resistant Surfaces to Highways," Paper presented at the 37th Highway Research Board Meeting, 1958.
30. Nichols, F. P., Dillard, J. H., and Alwood, R. L., "Skid Resistant Pavements in Virginia," Bulletin No. 139, Highway Research Board, 1956.
31. Normann, O. K., "Braking Distances of Vehicles from High Speed," Public Roads, Vol. 27, pp. 159-169, June, 1953.
32. Reed, J. C., "Fine-Aggregate Surfaces for Skid-Resistant Pavements," Paper presented at the Annual Meeting of the American Association of State Highway Officials, 1956.
33. Rice, J. M., "Highlights of Recent Activities at NCSA Laboratory," Journal, The National Crushed Stone Association, December 1955.
34. Rice, J. M., Discussion to paper, "Providing Skid-Resistant Roads in Virginia," Proceedings, The Association of Asphalt Paving Technologists, Vol. 26, pp. 19-21, 1957.

35. Ruefer, A. L., "Test Installations of Thin Silica Sand Asphalt Resurfacing," Paper presented to the 37th Annual Meeting of the Highway Research Board, 1958.
36. Sabey, B. E., "Accident Reports as a Guide to Slippery Length of Road," Roads and Road Construction, Vol. 34, pp. 203-6, July, 1956.
37. Schlesinger, G. F., "Design of Brick Surfaces to Obviate Slipperiness," Proceedings, Highway Research Board, Vol. 14, pp. 187-198, 1934.
38. Shelburne, T. E. and Sheppe, R. L., "Skid Resistance Measurements of Virginia Pavements," Research Report No. 5-B, Highway Research Board, 1948.
39. Shupe, J. W., "Factors Affecting the Skidding Resistance of Bituminous Pavements," A Thesis submitted to the University of California, Berkeley, for the degree of Master of Science, 1951.
40. Shupe, J. W., "Progress Report No. 5 on Skid Resistance Study for U. S. 31 Test Road," Report No. 36, Joint Highway Research Project, Purdue University, 1956.
41. Skeels, P. C., Stonex, K. A., and Finney, E. A., "Road Surface Friction from the Standpoint of Automotive and Highway Engineers," Proceedings, The Association of Asphalt Paving Technologists, Vol. 25, pp. 353-378, 1956.
42. Skeels, P. C., "Measurement of Pavement Skidding Resistance by Means of a Simple 2-Wheel Trailer," Paper presented at the 37th Annual Meeting of the Highway Research Board, 1958.
43. Stinson, K. W. and Roberts, C. P., "Coefficient of Friction Between Tires and Road Surfaces," Proceedings, Highway Research Board, Vol. 13, pp. 169-188, 1933.
44. Stinson, K. W. and Roberts, C. P., "Further Coefficient of Friction Tests," Proceedings, Highway Research Board, Vol. 14, pp. 131-147, 1934.
45. Stutzenberger, W. J. and Havens, J. H., "A Study of the Polishing Characteristics of Limestone and Sandstone Aggregates in Regard to Pavement Slipperiness," Paper presented at the 37th Annual Meeting of the Highway Research Board, 1958.

46. Thompson, H. O., "Road Tests Determine What Makes Autos Skid," Engineering News--Record, pp. 54, February 6, 1958.
47. White, A. M. and Thompson, H. O., "Test for Coefficients of Friction by the Skidding Car Method on Different Road Surfaces, Both Wet and Dry," Paper presented at the 37th Annual Meeting of the Highway Research Board, 1958.
48. Whitehurst, E. A. and Goodwin, W. A., "Pavement Slipperiness in Tennessee," Proceedings, Highway Research Board, Vol. 34, pp. 194-209, 1955.

APPENDIX A

Gradation of Abrasives Used in
Polishing Test Specimens

#3/0 Quartz:

U. S. Sieve No.	Percent Retained
100	0.0
140	6.4
170	9.3
200	18.0
270	18.9
325	18.2
Pan	29.2

#5/0 Quartz:

The only specification for this grade is that 80 percent will pass a No. 270 U. S. Sieve.

Limestone Mineral Filler:

State Highway Department of Indiana Specifications

U. S. Sieve No.	Percent Passing
30	100
80	95-100
200	65-100

The mineral filler used as a polishing agent had over 90 percent passing the No. 200 sieve.

APPENDIX B

A Petrographic and Megascopic Description
of the Mineral Aggregates Used in this Investigation

Information on each aggregate includes:

- | | | |
|--|----------------------------|--------------------------------|
| 1. Aggregate
Identification
Symbol | 2. Location
as to State | 3. A Megascopic
Description |
| 4. A Petrographic Description | | |

L-1 Indiana Fine-grained, light-grey limestone

A microcoquina limestone, consisting of fossil fragments in a diagenetic matrix of calcite grains. The brachiopod, crinoid, and bryozoa fragments vary in size from 0.1 to 0.4 mm. The calcite grains in the matrix are subround to subangular in shape and average about 0.2 mm in length.

L-2 Indiana Fine-grained, light-gray limestone with
 visible bedding

A crystalline granular limestone consisting of angular interlocking calcite grains. The grain size of the primary calcite is about 0.01 mm, while the narrower beds of coarser calcite consist of rhombs approaching 0.3 mm in length.

L-3 Indiana Medium crystalline buff-gray limestone,
 slightly porous

A crystalline granular limestone consisting of angular interlocking calcite grains. The primary grains are 0.04 mm in length with occasional pockets (about 10 percent) of coarse calcite grains 1 to 2 mm in size. There is a small amount of porosity with the voids averaging 0.1 in length.

L-4 Indiana A finely-crystalline porous brown-gray
 limestone

A crystalline granular limestone with interlocking grains 0.02 to 0.06 mm in length. Strongly euhedral rhombs of carbonate dominate the other angular crystals. There is a trace of subangular detrital quartz. There is also some porosity present (5 to 10 percent) in the form of voids from 0.1 to 0.2 mm in length.

L-5 Indiana Very fine-grained gray limestone

A very fine crystalline granular limestone with angular interlocking grains less than 0.01 mm in length. There is a trace of 0.1 mm quartz grains in evidence, but the primary constituent is fine-grained interlocking calcite grains.

L-6 Kansas Fine-grained, light-gray limestone with visible foraminifera tests

A fine-grained foraminiferal limestone consisting of approximately 60 percent calcite matrix and 40 percent foraminifera tests. The matrix is composed of subround to subangular uniform grains less than .01 mm in length, while the ovate foraminifera measure 4.0 mm in their major dimension.

L-7 Virginia Fine-grained, dark-gray limestone

A very fine-grained carbonaceous limestone with a ground mass of subangular calcite grains less than 0.01 mm in length. Also present (approximately 15 percent) are mosaic "pockets" of dark carbonaceous matter and calcite grains, 0.3 to 0.4 mm in length, which appear to be fossil fragments.

L-8 Virginia "Dense" gray limestone

A crystalline granular siliceous limestone consisting of angular quartz grains bound in a matrix of angular calcite grains. The matrix, composing 60 to 70 percent of the material, is made up of calcite grains 0.05 to 0.07 mm in length with a few rhombs present. The primary detrital mineral is quartz with the grains averaging from 0.1 to 0.3 mm in length. There is also a trace of feldspar present.

L-9 Virginia Fine-grained gray limestone with visible calcite crystal faces

A crystalline granular limestone with angular interlocking grains averaging 0.03 to 0.04 mm in length. There are a few irregular rhombs, as well as coarse calcite (0.1 mm) veins present.

L-10 Virginia Fine-grained gray limestone with white calcite veins

A crystalline granular limestone composed primarily of uniform angular crystals 0.01 mm in length. Wavy irregular bedding, 0.1 to 1.0 mm wide, is present consisting of coarse (0.1 mm) calcite grains.

L-11 Indiana Light-gray visibly oolitic limestone

A uniform oolitic limestone consisting of 60 to 70 percent of elliptical and rounded oolites bound in a granular matrix of calcite. The oolites are 0.4 to 0.5 mm in the major dimension, while the calcite grains are about 0.1 to 0.3 mm in length. There are traces of fossil fragments and detrital quartz present.

L-12 Indiana Light-gray crystalline limestone with
 some visible oolites

An oolitic limestone consisting of 50 to 60 percent of elliptical and rounded oolites bound in a granular matrix of calcite which contains appreciable amounts of detrital quartz and fossil fragments. The respective sizes of each of the components are as follows: oolites, 0.3 to 0.4 mm; calcite grains, 0.07 mm; quartz particles, 0.1 to 0.3 mm; and foraminifera, 0.3 to 0.4 mm.

C-1 Kansas Very fine-grained gray chert

A cryptocrystalline chert consisting primarily of very fine subround to subangular grains, approximately 0.005 mm in length, with a few patches of coarser (0.01 mm) chert grains.

R-1	Massachusetts	Fine-grained, dark-red felsite with visible feldspar phenocrysts
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A fine-grained porphyritic dacite containing plagioclase and quartz phenocrysts. The ground mass, consisting of 0.01 to 0.02 mm grains, constitutes about 80 percent of the material with the remaining 20 percent composed of phenocrysts, with grain size ranging from 0.5 to 1.5 mm. In addition some quartz is present along the flow bands, probably having formed during the post crystallization period.

Q-1 Maryland White quartzite pebble with some clear
 quartz grains

A white quartzite pebble consisting of granoblastic quartz in which the anhedral grains vary from 1 to 3 mm in length.

Q-2 Virginia Buff-stained quartz pebble

A single quartz pebble.

S-1 Indiana A medium-grained, buff-brown sandstone

A medium-grained friable sandstone consisting of well-sorted 0.5 to 1 mm subangular quartz grains with a small amount of limonitic cement.

S-2 Kansas Medium-grained gray limey sandstone

A calcareous sandstone in which the clastic quartz grains are bound in a matrix of calcite. The angular to subangular quartz grains are from 0.1 to 0.5 mm in length and constitute about 60 percent of the material. The remainder is primarily a calcite cement, with grains 0.1 to 0.3 mm in length, with traces of microcline, plagioclase, quartzite or chert, and dark carbonaceous matter.

D-1 Virginia A fine-grained gray dolerite with visible plagioclase

A hypidiomorphic granular dolerite with the grains, which average from 1.1 to 1.2 mm in length, forming "teepee" structure. The primary minerals are labradorite and augite with less than five percent of magnetite present. There is a slight development of epidote from the post crystallization period.

D-2 Virginia Dark Fine-grained dolerite

A hypidiomorphic granular dolerite with the grains, which average from 0.07 to 0.14 mm in length, forming "teepee" structure. The ground mass consists of interlocking crystals of labradorite and augite, with occasional plagioclase phenocrysts 0.7 mm in length. There are traces of olivine, apatite, magnetite, and chlorite.

G-1 Virginia A fine-grained, gray-green granite with visible quartz and mica

A hypidiomorphic granular biotite-granite with some parallel arrangement of large mica crystals averaging 1.4 mm in length and a small amount of recrystallized grains 0.05 mm in length concentrated along the shear lines. The mineral composition consists of 50 to 60 percent microcline with 25 percent quartz, 10 to 15 percent biotite, and traces of apatite, zircon, epidote, and muscovite.

SL-1 Indiana Light-gray vesicular glass (slag)

A vitrophyric glass with a small amount of silicate microlites. There is a vesicular structure with the circular vesicles, which constitute from 10 to 20 percent of the material, varying from 0.1 to 0.5 mm in diameter.

VITA

John Wallace Shupe was born on March 30, 1924, in Liberal, Kansas.

He entered Kansas State College in 1941. During the years 1943 to 1946 he served in the 8th Air Force as a navigator. He returned to Kansas State College in 1946 and received the degree of Bachelor of Science in Mechanical Engineering in 1948.

After serving as instructor in the Applied Mechanics Department at Kansas State College for one year, he accepted a position at the University of California at Berkeley as Lecturer in Civil Engineering and Junior Engineer in the Institute of Transportation and Traffic Engineering. He received his Masters degree in Civil Engineering from the University of California in 1951.

He returned to Kansas State College in 1951 as Assistant Professor in the Applied Mechanics Department and was elevated to Associate Professor in 1954. He was on leave of absence from Kansas State College while continuing his graduate work at Purdue University. During the 1956-57 academic year he received a Danforth Faculty Fellowship, and during 1957-58 a National Science Foundation Faculty Fellowship.

He is a member of Pi Tau Sigma, Chi Epsilon, Sigma Tau, Sigma Xi, the American Society of Civil Engineers, and the

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His publications are:

Moyer, R. A., Gallagher, P. D., and Shupe, J. W.
"A Rating Method for Resurfacing the Secondary Street System in Berkeley", Proceedings, The Second California Institute on Street and Highway Problems, 1950.

Moyer, R. A. and Shupe, J. W. "Roughness and Skid Resistance Measurements of Pavements in California", Bulletin No. 37, Highway Research Board, 1951.

Shupe, J. W. "Instilling Desire for Student Self-Improvement", Journal of Engineering Education, Vol. 44, No. 3, Nov. 1953.

Shupe, J. W. and Taylor, E. C. "Field and Laboratory Investigations on Hot Mix Asphalt Concrete", Bulletin No. 154, Highway Research Board, 1956.

